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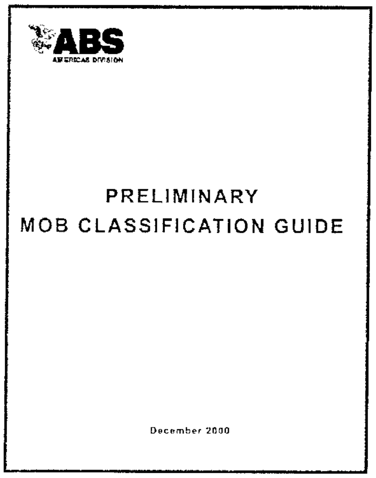
ABS
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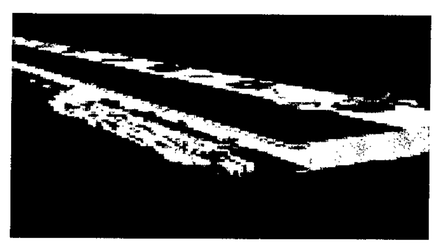
PRELIMINARY
MOB CLASSIFICATION GUIDE

December 2000

Mobile Offshore Base (MOB) Science and Technology Program Final Report

by
MOB Project Team

December 2000



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13. ABSTRACT (Maximum 200 words)

This report summarizes the Science and Technology Program conducted by the Office of Naval Research to investigate the feasibility and cost of a Mobile Offshore Base (MOB). A MOB is envisioned as a self-propelled, floating platform, comprised of one or more serially connected modules which can be assembled as necessary to support U.S. military operations in areas where fixed bases are unavailable or inadequate.

The fact that a MOB is unprecedented in functionality and size (up to 6,000 feet in length to operate conventional cargo aircraft) required advancements spanning mission planning to design to fabrication. This three year program used experts from over 50 commercial, academic, and government agencies for both research and quality control. Key products include: a Preliminary MOB Classification Guide, next generation hydroelastic seakeeping models, a metocean environmental specification, a physics-based Operational Availability model, four preliminary platform designs, and hardware advancements in connector and dynamic positioning technologies. All of the S&T studies are described and referenced.

It is concluded that MOB semisubmersible modules can be built today, and that a mile-long multiple-module MOB is technically feasible pending completion of some uncompleted studies. Acquisition cost for a 5,000 foot platform was estimated at between $4B and $8B.

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Executive Summary

Synopsis

This report summarizes the three-year Science and Technology (S&T) Program conducted by the Office of Naval Research (ONR) to investigate the feasibility and cost of a Mobile Offshore Base (MOB). In concept a MOB is a self-propelled, floating platform comprised of one or more serially connected modules which can be assembled as necessary to support U.S. military operations in areas of the globe where fixed bases are either not available or are inadequate. The objective of this Program was to estimate costs and feasibility for these unprecedented structures.

The present interest in offshore basing is motivated principally by the steady decline in long-term access to U.S. overseas bases such as airfields, shipping ports and logistics facilities. This affects a wide range of missions with military, diplomatic, political, and economic implications, ranging from peacetime (e.g., overseas presence, humanitarian operations, training, and prepositioning) to hostilities (e.g., counter-terrorism, special operations force operations, non-combatant evacuation operations, and lesser and major regional contingencies). A second motivating factor relates to recognized deficiencies of present amphibious and prepositioning logistics assets to satisfy emerging power projection and sustainment strategies (e.g., Operational Maneuver from the Sea). A third factor relates to declines in overseas repair and replenishment capabilities for Fleet assets. Finally, an offshore base offers certain advantages compared to land bases with respect to vulnerability to terrorist actions.

In response to these issues, a 1995 MOB Mission Needs Statement (MNS)[1] was prepared but never formally approved. Nonetheless, this draft document established a framework of operational requirements that was used to guide this Program. The mission needs address a system envisioned to provide the following capabilities:

- An advanced base for air, land, and naval expeditionary forces.
- An in-theater command, control, communications, computer, and intelligence (C4I) capabilities to a Joint Task Force (JTF).
- A tactical aviation operation and support base for conventional takeoff and landing (CTOL), short takeoff and landing (STOL), vertical/short takeoff and landing (VSTOL), and rotary wing aircraft.
- A base capable of launching and recovering Special Operations Forces (SOF) missions.
- An alternative capability to land-based naval advanced logistic support sites and naval forward logistic sites, to include refueling and re-supply of military units.
- Supplemental or alternative mobile pre-positioning of military combat, combat service, and combat service support equipment and supplies.
- An inter-theater and intra-theater logistics node supporting movement of both pre-positioned and deployed equipment and supplies.
- A transportation node capable of supporting routine movement of combat and transportation assets.

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[1] A preliminary Mission Needs Statement for the Mobile Offshore Base (MOB) ACAT Level 1 was published 15 September 1995, but not JROC approved.

- An in-theater organizational, intermediate, and selected depot maintenance and repair facility supporting deployed air, sea, and land systems.

A single system capable of satisfying this extraordinarily broad list of objectives was clearly large, unprecedented, and beyond the industry state-of-practice. And the fact that the MNS did not identify specific MOB missions added more uncertainty about the nature of these proposed multi-functional platforms. That made it imperative to perform a critical evaluation of the MNS to identify a general scope and bounds for this Program. Specific findings from that process were:

- *A modular platform architecture was necessary to allow for maximum mission flexibility and economy.*
- *A single 1000-1200 foot long module would satisfy most of the mission objectives identified in the MOB MNS.*
- *Satisfying <u>all</u> of the mission objectives would require a platform up to 6000 feet in length,* driven solely by the requirement to operate conventional take off and landing (CTOL) aircraft. (This Program did not factor in uncertain, revolutionary advances in future aircraft capabilities that could significantly shorten this runway requirement.)
- *The Program would advance proposed module designs only if they were capable of operating both individually <u>and</u> serially aligned as part of a longer platform* (with an as-yet unspecified connectivity scheme). Therefore, this eliminated module concepts that were operationally and/or economically optimized to support only one particular mission. The most important consequence of this was that it led to the Program consensus that semisubmersibles were clearly superior to conventional displacement hulls. Certainly, displacement hulls are legitimate and economical candidates, but they were rejected for several reasons. They have an unacceptably narrow beam for incorporation as part of a C-17-capable platform, and they have inherently larger wave-induced motions compared to a semisubmersible, which makes the connector design unnecessarily more difficult and adds significant risk. Regarding transit speeds, semisubmersibles have only a marginal disadvantage compared to traditional displacement hulls because they can attain nominal transit speeds of 15 to 18 knots in the deballasted mode.
- The lack of precedents for long, multifunctional, serially-connected platforms operating and surviving in the open ocean dictated that the thrust of this Program be the *fundamental advancement of all technologies necessary for the design, construction and operation of this new class of structure*.

It was clear that industry did not have adequate tools to reliably design a MOB when this Program began in 1997. However, through the efforts of over 50 performing organizations from industry, academia and government, working collaboratively in an open program, the key issues that put MOB beyond the state-of-practice have been or can be resolved. These advances are fully described and documented in this report. Final recommendations to complete the S&T advancements are outlined.

Technical Focus of Program

At the inception of this Program there were (and still are) no precedents for multiple-module platforms of

any comparable length operating and surviving in the open ocean. More specifically, a large number of critical supporting technologies were either absent or deficient for design, including:

- Guidelines for safely operating conventional fixed wing aircraft from a finite-sized, floating airfield
- Design standards and computer models applicable for identifying the structural adequacy and stability of multiple-module platforms.
- Manufacturing and construction experience with large-sized components considered appropriate for such platforms.
- Description of the metocean environment, particularly ocean waves, appropriate for the 6,000-ft platform.
- Experience in connecting and operating multiple floating bodies in close proximity in the dynamic ocean environment.

This list encompasses a broad range of technologies. This Program obligated $37 million over a three-year period, including over 75 contracts and grants, to advance as many of the technologies as possible to a level adequate for MOB design. All of the Program studies were organized into one of four development product areas. Objectives and sample advances for each area are:

1. **Mission Requirements and Performance Measures.** The first focus was on developing tools to convert military/mission objectives into engineering design criteria. For example, a rational methodology was developed for (1) defining MOB design criteria from any set of mission requirements, then (2) documenting and tracing the criteria with a hierarchical database. Also, studies were made to determine key design criteria, such as transit speed and allowable dynamic runway motions during air operations. The second focus was on development of physics-based tools to quantify how well a given design would satisfy the military requirements for a given site and season. For example, reliability-based, performance-measuring tools were developed to rigorously assess the relative mission effectiveness of candidate platform designs. This product area is discussed in Section 2.1 and in Appendix A.

2. **Standards and Criteria.** Because there are no existing design standards for a structure as unique and as large as the MOB, it was necessary to return to engineering fundamentals for the development of the *MOB Classification Guide and Commentary*. The *Guide* addresses hydrodynamic stability and structural integrity, and encompasses the design methodology, environmental criteria, stability requirements, and survivability requirements necessary for insuring the integrity of a MOB platform. The *Guide* uses a performance- and reliability-based approach, and is a living document that is expected to evolve. This product area is discussed more thoroughly in Section 2.2 and Appendix B.

3. **Design Tools.** The S&T Program supported major advances in stability and hydroelastic numerical modeling of floating offshore structures. Existing hydrodynamic codes have been expanded and accelerated by orders of magnitude, including the development, improvement, and integration of hydroelastic and structural programs. Three sets of experiments were completed to obtain validation data. These new programs have been partially verified, but due to the short Program duration it was not possible to rigorously validate all of them using the new data. These advances are described in Section 2.3 and Appendix C.

4. **Alternative Concepts.** This product area concentrated on (1) characteristics associated with candidate architectures for the longest MOB platform, and (2) other component design issues such as

connectors, cargo handling, and dynamic positioning. Four unique, innovative, MOB platform concepts were developed through preliminary design to establish feasibility, uncover technology problems, and support realistic cost estimating. The first three concepts explored different connectivity schemes, while the fourth evaluated an alternative construction material. The concepts, along with the designers, were:

- McDermott Technology, Inc. Five identical, 1,000-foot, steel semisubmersibles, connected using centerline ball joints and flexible edge connectors.
- Kvaerner Maritime. Three 800-foot, steel semisubmersibles, connected by two 1,250-foot, flexible bridges that act like distributed connectors, including motion damping.
- Bechtel National, Inc. Three identical, 1,650-foot, steel, independent semisubmersibles that rely on dynamic positioning to maintain runway alignment.
- Aker Engineering. Four identical, 1,250-foot, steel-deck, concrete-pontoon semisubmersibles that use elastomeric connectors.

Each builder provided additional development in component areas of concern, such as connectors (McDermott), dynamic positioning (Bechtel), concrete (Aker), and damping (Kvaerner), which could be leveraged to the other design concepts. All concepts are still viable candidates for MOB, each with their own advantages and design challenges. Illustrations and additional information on these concepts are provided in Section 2.4 and in Appendix D.

Program Conclusions

Feasibility. This Program identified and managed an extensive series of advancements using the best of academia, industry, and government experts. And while there were many *specific* achievements, the proper measure of the Program's success is how the *collective* advancements contributed to the Program objective of estimating cost and feasibility for MOB. An independent group of marine engineering experts from industry, the American Bureau of Shipping, and academia was tasked to review the Program and its products and render an opinion on MOB feasibility and cost. The resulting assessment report was provided to Congress in April 2000 (Cheung and Slaughter, 1999; see Section 5 for References). A key conclusion was that all of the key technology issues identified at the inception of the ONR S&T program that put MOB beyond the state-of-practice were either resolved or evaluated sufficiently to conclude there were no inherent showstoppers.

There are two criteria for feasibility. A *necessary* characteristic was that the candidate platform be survivable to all natural and hostile threats. A *desirable* characteristic was that the platform accomplish all of the mission requirements – in other words, be fully functional. These criteria were assessed using the following process:

- Nominal platform dimensions were obtained by deconstructing representative MOB missions into associated design criteria and conducting supplemental studies into airfield operations, cargo transfer, transit speed, and general utility.
- A comprehensive design procedure was developed to ensure structural reliability and stability, including a preliminary metocean (wind, waves, current) specification at the unprecedented scale of the longest MOB platform. Hydrodynamic analysis tools were developed or improved to a degree sufficient for MOB design.
- Four candidate connection schemes were identified through preliminary platform studies. Construction procedures were advanced and were concluded to be within the capabilities of the

shipbuilding industry. All four concepts feature different advantages and design challenges.

These studies lead to the following conclusions regarding feasibility:

- Single MOB semisubmersible modules can be built today (nominal length to 1,200 feet).
- Short MOB platforms consisting of two or three connected semisubmersible modules (platform lengths up to 3,000 feet) are feasible.
- The longest 6,000-foot MOB supporting full CTOL operations is feasible, pending completion of the remaining S&T. All four candidate platform architectures are candidates pending final sizing of the platform based on an Operational Requirements Document.

Cost. Only approximate cost estimates are possible for a novel structure such as MOB because there is no definitive MOB Operational Requirements Document (ORD). For example, if the mission requirements exclude CTOL operations, the most economical option would most likely be a MOB comprised of multiple, separate modules. Requiring CTOL amplifies the cost for most of the multiple platform candidate architectures due to the connectors and strengthened modules to accommodate the connector loads. Without a definitive ORD, the four system design contractors were asked to estimate construction costs for a nominal, CTOL-capable, 5,000-foot platform, built to a commercial level of construction (complete structure, machinery, and outfit, but no military systems). Those four estimates ranged between $5 billion and $10 billion. Not all of the designs were equal and some estimates included design and facility costs. A second set of independent estimates was made by extrapolating from present practice for basic hull construction only, and ranged from $3.8 - $5.3 billion to $6.0 - $7.4 billion (University of Maryland and Band Lavis and Associates, respectively). Based on this information and general experience,

- *The cost of bare bones, 5,000-foot platform is likely to range between $4 billion and $8 billion.*
- *The cost of a single 1000-1200 foot MOB (semisubmersible) module would be about $1.5 billion.*

Note that the cost of a single MOB semisubmersible module is in fact quite comparable to other, more conventional, proposed, displacement hull designs (e.g., LHA). Also, the use of a MOB would avoid nonrecoverable costs associated with building and abandoning temporary land bases such as Somalia and Bosnia. It is also pointed out that the rapid response possible with relocating a "ready-to-use" MOB versus the time required to construct or upgrade new, temporary terrestrial facilities has added military value that is difficult to quantify. Additional information regarding feasibility and cost is available in "The MOB S&T Program: An Independent Review" (December 1999), which was authored at MCA Engineers, Newport Beach, CA.

Key Program Products

At the inception of this Program there were no standards, experience, or tools adequate for the design of multiple-module, connected, open ocean platforms. Even the nominal length of single MOB semisubmersibles was 50% longer than the state-of-practice. Those deficiencies served as the basis for defining the scope and breadth of this ONR Science & Technology Program. The studies were kept as generic and fundamental as possible to maximize universal applicability to as many mission scenarios, module hull types, and platform configurations as possible. Collectively, these advancements served as the basis for the feasibility conclusions discussed in the previous Section. Some of those major technology advancements include:

- ***Preliminary MOB Classification Guide.*** The size of the individual modules, and size and uniqueness of the connected platforms, make them both marine structures without precedent. This demanded a *Guide* based on engineering fundamentals rather than the typical approach of extrapolating from past experience. The MOB *Guide* addresses all aspects of design and construction such as structural integrity, stability, and vulnerability. A performance- and reliability-based framework was chosen, which is the first of its kind for the certification of offshore structures in the U.S.
- Advancement of ***hydroelastic seakeeping models*** for estimation of the coupled dynamic system consisting of dynamic connector loads, module/runway structural responses, and the wave field (which affects at-sea cargo transfer operations). These models span the design process from preliminary to final design, and are crucial to the tractability of the reliability-based procedures for fatigue and survival studies required in the *Guide*. In addition, three validation experiments were completed for (1) dynamics of a four-module platform; (2) air gap under a single module; and (3) dynamics of a single module at the transit draft.
- Preliminary ***metocean environmental specification***, which is appropriate for the unprecedented scale of the full CTOL platform. This includes: (1) a hindcast database of wind/waves/current conditions for 20 years, averaged over 6 hour intervals, at 25 sites worldwide, and (2) an engineering description of various local metocean phenomena such as hurricanes and internal waves. Multiple pioneering studies were initiated addressing the important topic of spatial coherence of ocean wave fields at the one-mile scale. This specification is crucial to the probability-based design procedures in the *Guide*.
- ***Operational Availability model*** that quantifies mission performance for a given platform, site, and season. This physics-based model uses precomputed data regarding seakeeping behavior of both the platform and a cargo ship of interest, cargo transfer rates as a function of crane dynamics, the metocean database for a site and season of interest, and the mean time between failures and repair times for key subsystems. As one example, it can be used to calculate statistically reliable estimates of system capabilities such as effective cargo throughput, fuel requirements for the dynamic positioning system, etc. Similar throughput can be estimated for air cargo and even other non-MOB operations.
- ***Four preliminary platform designs*** based on three distinct connection schemes and one alternative hull material (reinforced concrete for lower hulls). While these important studies were preliminary only, their findings have increased confidence that there are no major technical showstoppers for connected MOB platforms.
- Advancement of ***MOB component hardware*** such as candidate connector concepts and control strategies for multiple-module dynamic positioning. Multiple studies have yielded complimentary contributions to this important technology area that is arguably the most influential factor regarding the feasibility of the entire modular approach.

An important consequence of the fundamental nature of this S&T Program is that the results are applicable to all large floating platforms, regardless of hull shape, including commercial facilities related to open ocean air- and sea-cargo hubs.

Unfinished Business

It was not possible to eliminate all of the technical uncertainty for platforms as unprecedented as a full-length, multiple-module platform during this three year S&T program. Some of the remaining major issues recommended for further study are listed below.

- ***User involvement.*** MOB development in this Program was based on the 1995 preliminary MOB MNS. That document included a wide range of missions but it was primarily prescriptive in nature. The shifting nature of world politics and military development makes it difficult to develop a precise performance document. "Customer" involvement in the development process can only improve the quality of cost estimates and improve the focus of technical development. The joint MOB (JMOB) studies underway at the Institute for Defense Analysis, with report due to Congress by March 2001, may provide some answers here.
- ***Global response evaluation.*** Studies in this technology topic started with improvement of the state-of-the-art in hydrodynamic and hydroelastic analyses, and finished with completion of a series of hydroelastic laboratory-scale validation tests. However, there was not sufficient time to analyze the data or to use it to validate the new models. *This is arguably the single most important outstanding technology issue from this S&T Program.* Validation of these global models is essential to minimize uncertainty about the connector loads and global responses while in the connected configuration.
- ***Cargo Transfer.*** The movement of cargo from MOB to shore is considered the logistic requirement with the most uncertainty. Additional S&T work is required to quantify the required cargo transfer rates, to identify and improve the ability of cargo handling equipment to transfer cargo from MOB, to quantify the capability of those transport craft for typical MOB stand-off distances, and to develop concepts for rapid transfer of material from MOB to shore.
- ***Classification Guide.*** The present preliminary version of the comprehensive *Guide* could not be completed within the time frame of this Program. Further development is necessary to quantify many of the parameters, such as the partial safety factors, and to incorporate the results from other uncompleted tasks such as wave coherence (see below).
- ***Dynamic Positioning.*** The cruise industry is advancing the development of azimuthing thrusters, and the offshore industry has continued improvements in the control of multiple thrusters for maintaining station with respect to a fixed reference. The MOB S&T Program used both of these advancements and further pioneered technology for multiple module stationkeeping and for the connection maneuvers among the modules. This effort needs to continue, with an emphasis on failure tolerance and reliability.
- ***Connectors.*** At the beginning of the Program, concerns were raised about the capacities of connectors to withstand the very large loads predicted by experiments conducted under a previous DARPA program. As a result platform designs have evolved towards extremely flexible connectors that trade increased relative motions for greatly reduced loads. While the industry opinion is that these connectors are feasible, they need to be demonstrated at operational scale.
- ***Metocean Environmental Specification.*** The accuracy of motion and load simulations for the longest connected platforms depend equally on the accuracy of: (1) the global response models and (2) the wind/wave/current excitation at that unprecedented scale. As described above, this S&T program produced a preliminary engineering specification for the environment at such scales, but some critical work remains, particularly for large-scale wave coherence. Completion of these pioneering studies (spanning from extreme/hurricane to swell wave conditions), along with validation of the global response models (listed above), are absolutely necessary in order to get accurate force maximum and fatigue estimates for elastic connector design.
- ***Exercise Classification Guide with more credible mission requirements.*** In addition to the *Guide* completion recommended above, it is strongly recommended to directly evaluate the final *Guide* with a representative platform design, perhaps based on a user defined statement of mission requirements. This critical evaluation of the final *Guide* would jointly verify the whole

MOB design package consisting primarily of the *Guide*, the new hydroelastic tools, and the statistical/ probabilistic metocean environmental specification.

- ***Validate the MOB design process at larger scale.*** The Program conclusion of MOB feasibility is based on numerical analysis, laboratory and small scale testing, and the experience of the offshore industry. If the U.S. decides that MOB provides a credible and needed capability, the technology should be verified and validated at larger scale as part of a normal risk reduction program.

1 INTRODUCTION

This objective of this **MOB Final Report** is to provide a comprehensive and definitive summary of the conclusions and technical accomplishments achieved during the FY97-00 Mobile Offshore Base Science and Technology Program managed by the Office of Naval Research. The report is organized as follows:

- An *Executive Summary* that summarizes the conclusions and major advancements.
- This *Main Report* that spans the entire Program, including MOB utility, technology gaps at Program inception, major technology advancements, Program schedule and funding, Program conclusions regarding feasibility and cost (Section 3), and remaining technical tasks.
- Four *Technical Appendixes*. Each Appendix is a moderately complete description of the respective technology areas, including justifications, approaches, achievements, and documentation for each sponsored study. References are provided for all studies.

All sections draw heavily from the *Independent Review of the MOB Program*[2], which provides further details about this Program and briefly describes the three-year effort focused on establishing the technology necessary to assess MOB feasibility and cost.

1.1 Background

As a global power, the United States employs a variety of means to fulfill its obligations and protect its national interests. The ability to project combat power rapidly to widespread areas of the globe, such as with Naval Carrier Battle and Marine Expeditionary Groups, is a cornerstone of the U.S. military preeminence and political influence in the world. However, recent events have shown that U.S. forces' long-term access to forward bases, including air bases, shipping ports and logistics facilities, can no longer be assured.

In response to these issues a 1995 MOB Mission Needs Statement (MNS) was prepared but the Joint Requirements Oversight Council (JROC) did not formally approve it. Nonetheless, this Preliminary MNS provided the basis of the ONR MOB program. The mission needs address a system envisioned to meet the following objectives:

- Provide an advanced base from which air, land, and naval expeditionary forces can conduct operations complementary to, or independent of, host-nation support.
- Provide an in-theater command and control (C2) center and operations facility directing and supporting air, sea, and land systems and providing command, control, communications, computer, and intelligence (C4I) capabilities to a Joint Task Force (JTF).
- Provide a tactical aviation operation and support base for conventional takeoff and landing (CTOL), short takeoff and landing (STOL), vertical/short takeoff and landing (VSTOL), and rotary wing aircraft. This base should support Joint Advanced Strike Technology (JAST) aircraft operations.
- Provide a base capable of launching and recovering SOF missions employing SOF aircraft and

[2] Mobile Offshore Base Science and Technology Program: An Independent Review, MCA Engineers, December 20, 1999.

maritime assets.

- Provide supplemental or alternative capability to land-based naval advanced logistic support sites and naval forward logistic sites, to include refueling and re-supply of military units.
- Provide supplemental or alternative mobile pre-positioning of military combat, combat service, and combat service support equipment and supplies.
- Provide an inter-theater and intra-theater logistics node supporting movement of both pre-positioned and deployed equipment and supplies to required locations via both sealift and airlift assets.
- Provide a transportation node capable of supporting routine movement of combat and transportation assets, including current and future U. S. and allied commercial and military air and sea transports (including C-17) and combat and surveillance aircraft and ships.
- Provide in-theater organizational, intermediate, and selected depot maintenance and repair facility supporting deployed air, sea, and land systems.

1.2 Mobile Offshore Base Concept

One possible solution to this problem of declining foreign bases is the Mobile Offshore Base (MOB). In concept, a MOB is a self-propelled floating, logistics platform consisting of one or more serially connected modules, which would transit to and operate in a variety of sites for peacetime missions, as well as provide critical support within or near areas of regional conflicts.

As presently envisioned, a MOB would support a wide range of missions. The most demanding mission would be as a replacement for a full-service forward logistics land base. Draft operational requirements given in the 1995 MOB MNS collectively imply or state that a full capability MOB platform has the following features:

- Length of up to 6000 feet,
- Low wave-induced dynamics to support conventional take-off and landing (CTOL) cargo aircraft operations (including the C-17) through Sea State 6,
- Open-ocean ship-to-MOB and MOB-to-lighterage cargo transfer through Sea State 3,
- Platform survivability in any incident storm (e.g., hurricane and typhoon),
- Large internal volume (at least 5,000,000 sq. ft.) for storage and aircraft hangering,
- Maintainability of 40 years between overhauls,
- Personnel safety issues associated with supporting a full Army brigade,
- Multiple mission functions, and
- Long-term stationkeeping in deep water.

Furthermore, the MOB MNS envisions a modular approach, "with the capability to adjust size and/or length to allow maximum flexibility in employment and deployment. A variety of functional configurations should be supportable. Modularity must allow operation as independent MOB units, as a full CTOL-capable MOB with C4I capability, or as an intermediate size MOB composed of any number of individual MOB units."

Broadly speaking then, the largest CTOL- and logistics-capable "full" MOB platform is best described as:

- comprised of serially aligned modules,

- up to 6,000-foot in length, and
- capable of operating and surviving at any open ocean site worldwide.

1.3 Foundation of the MOB Science and Technology Program

This program followed the FY93-95 Maritime Platforms Technology (MPT) Program, sponsored by the Defense Advanced Projects Research Agency, which included enabling MOB technologies. The MPT Program objective of conducting a MOB Advanced Concept Technology Demonstration (ACTD) was redirected to this Science and Technology (S&T) objective by the Chief of Naval Operations in the spring, 1996. Accordingly, the Office of Naval Research (ONR) assumed leadership to conduct the MOB Program to advance critical technologies essential to such a structure. The formal objective of this ONR S&T Program was ***to establish the feasibility and cost of the Mobile Offshore Base***; i.e., to determine whether MOB represents an effective, affordable, and reliable option for the United States.

At the inception of the ONR MOB program, there were many deficiencies regarding the capability to design a MOB to safely operate and survive in the open ocean. The accuracy of global response models (i.e., motions and loads in the connected configuration) was suspect because the available hydrodynamic analysis tools were not mature. The nature of ocean wave fields on a one-mile scale had not been studied. Key performance parameters such as transit speed, allowable relative module motions, and required cargo transfer rates had not been quantified. Tools were not available for quantifying and comparing MOB design concepts with each other or with anticipated mission requirements. Connection and stationkeeping systems of the size and complexity required for MOB were unprecedented. There was little consensus or analytical methodology to design, down select, build and operate a structure of the size and multifunctional requirements envisioned for MOB.

Designing and building a marine platform as revolutionary in size and function as a MOB is contrary to the conservative and evolutionary approach favored by the offshore community. This caution was echoed in the report "Assuring the Safety of Innovative Marine Structures," (National Research Council, 1991), which defined an innovative structure as:

> *"... a structure that requires analysis and/or special fabrication and inspection controls beyond those required by existing rules. Moreover, an innovative structure is usually the first of its kind; few, if any, design standards directly apply and there is little operational experience to relate directly to the design review process"*

This definition of an innovative structure clearly applies to the MOB. Recommendations in this NRC report led to the MOB S&T Program emphasis on the *MOB Classification Guide*, design tool development, and the advancement of representative system concept designs. The latter was considered the only effective way of uncovering problems and obtaining realistic costs. The NRC also concluded that the technical evaluation of such structures must be based on fundamental engineering principles, requiring engineering specialists with expertise in the relevant disciplines. That strategy was adopted in the MOB Program, which was implemented by over 50 performing organizations from industry, academia, and government working collaboratively in an open program.

1.4 Program Implementation

Code 334 (Ship Structures and Technology) at ONR managed the MOB S&T Program. Technical support and day-to-day administration was provided by the Naval Facilities Engineering Service Center in

Port Hueneme, California.

The program was managed with an "open forum information exchange" architecture to encourage the exchange of ideas and technical expertise. Features of this approach include:

- An unclassified web site (http://mob.nfesc.navy.mil), available to all program participants, that contains all reports, meeting minutes, presentation slides, and other project documentation
- Semi-annual technology exchange conferences where government personnel and program contractors present key information and results to date
- A technical quality control program organized in accordance with recommendations from Standard for Independent Project Peer Review3, which includes elements such as:
  - Periodic contract reviews by ONR and NFESC technical personnel
  - Independent "Peer" review by outside technical experts
  - Working Groups to guide technical development in product areas such as connectors, Standards & Criteria, design (hydrodynamic) tools, wave coherence, and dynamic positioning.
- Leveraging of technology developments. Key technology issues (e.g., connectors, air operations, dynamic positioning, etc.) that had broad application to all of the concepts being developed were investigated by a single organization. These organizations were selected based on level of expertise and past experience. The results of these investigations we then immediately made available to all program participants through briefings at working group meetings and posting of progress and technical reports to the web site.

[3] American Society of Civil Engineers, April 1997. This document is relevant to MOB because it is tailored to large civil engineering construction projects, such as dams and power plants. It emphasizes all aspects of a project, including safety, constructability, design criteria, failure modes, and cost.

2 MOB SCIENCE AND TECHNOLOGY PROGRAM

2.1 Introduction

The technical breadth of the ONR MOB S&T Program encompassed all technologies considered vital to achieving the Program objective, ranging from mission planning to reliable design and construction. The advances from this Program were kept as generic as possible to maximize applicability, with an emphasis on models and validation rather than quantitative studies. Accordingly, the products can be used not only to design MOB platforms for a wide range of scenarios, but they also apply to connected military lighterage and commercial large floating structures. The Program products consist primarily of reports, numerical models and experimental data.

The MOB S&T Program goals were to: (1) establish feasibility and cost, (2) identify shortfalls and advance the state-of-the-art in a consistent technology development program, and (3) demonstrate the overall state of industry by advancing a few promising MOB system concepts through preliminary design.

As shown in the following list and in Figure 1, all technical work was categorized into one of four general product areas:

- Mission Requirements and Performance Measures (Military planning and evaluation),
- Standards and Criteria (MOB Classification Guide),
- Design Tools (Validated computer simulation models used in the Guide), and
- Alternative Concepts (Components and overall system configurations).

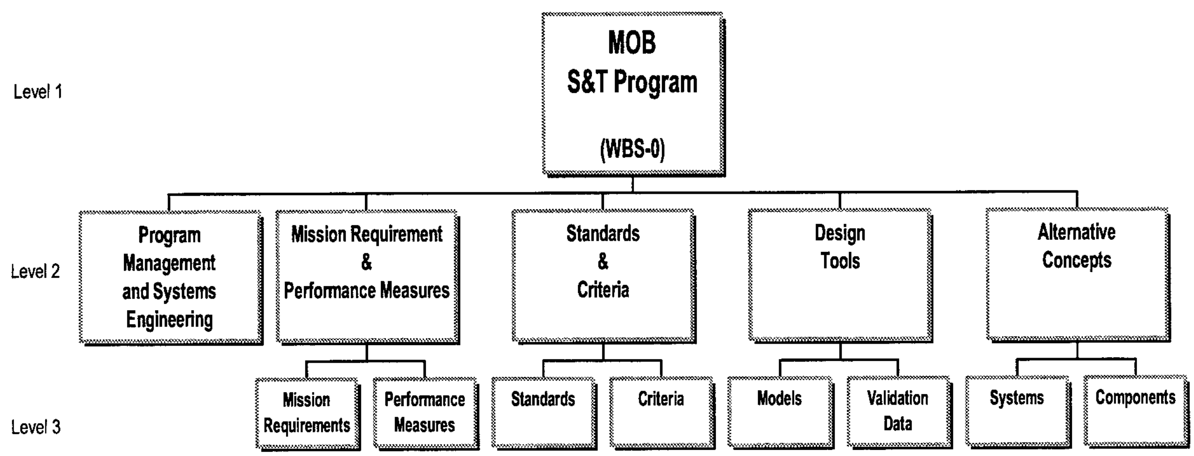

Figure 1. MOB S&T Program Work Breakdown Structure.

Table 1 lists all of the major program technical thrusts with their associated product areas, which were identified and pursued in this ONR program.

Table 1. MOB Program Task Summary.

Technology Thrust/Risk Area	MOB Product Area
Develop a range of representative MOB missions. Develop a process for converting mission requirements to engineering design parameters. Quantify air operations requirements for CTOL aircraft. Develop a sea-based cargo throughput model. Develop an operational availability model to statistically quantify platform performance. Develop a general model for estimating costs	**Mission Requirements and Performance Measures** (Appendix A)
Develop a ***MOB Classification Guide.*** Assess survivability/vulnerability. Advance fracture mechanics model for connector fatigue. Compile comprehensive environmental specification. Investigate ocean wave field characteristics.	**Standards and Criteria** (Appendix B)
Evaluate and advance hydromechanics models (seakeeping, wave field, and transit dynamics). Perform hydromechanics validation	**Design Tools** (Appendix C)
Advance four candidate platform configurations through preliminary design. Advance connector technology. Advance station-keeping technology (dynamic positioning and mooring).	**Alternative Concepts** (Appendix D)

Many Program accomplishments have been published in the open technical literature, climaxed by over 60 papers at the Very Large Floating Structures Conference, held in Hawaii in September 1999. In addition, over 350 technical documents generated by the MOB program are freely available at the MOB Internet site, http://mob.nfesc.navy.mil.

The **Executive Summary** listed a number of descriptors enforced on all of the S&T studies. Three of the more important ones are described below.

1. It is important to remember that there is no single definition of "a MOB". It is more accurate to view "MOB" as a collection of many possible platform configurations and lengths comprised of one or multiple modules (either identical or different). This provides flexibility in meeting particular mission requirements.

2. The modular architecture described above introduces the need for connectors, which are arguably the single most challenging and presently risky aspect of a MOB design. As described later, preliminary platform design studies were conducted for platforms based on four general categories of connection schemes:

    - Rigid Connectors (limited studies; presently considered viable only for inter-theater 2,500 foot length platforms)
    - Flexible, Discrete Connectors (hinge, ball joint, gimbal, elastic mounts, etc.)
    - Flexible, Distributed Connector (very long and flexible "truss bridge" between or outboard of MOB modules)
    - Dynamic Positioning (no structural connection)

    Further work is required in all of these approaches. However, no showstoppers were encountered with any of them.

3. The hull form selected by all of the contractors in this Program was the semisubmersible. Each module would have a nominal 700-1600 foot length, designed for independent or serially connected operations. They would transit to site in a deballasted mode on the pontoons (hydrodynamically equivalent to a catamaran) at nominally 15^{+} knots with a full cargo payload. The semisubmersible hull form was favored over traditional displacement hulls, since it is much more stable for open ocean air and cargo operations. Its inherent stability leads to significantly lower loads in the module connectors, and it naturally provides the very wide beam (nominally 450 feet) required providing parallel CTOL runway and unloading areas.

    The overwhelming consensus opinion of the participants regarding ship versus semisubmersible hull types in this Program was:

    - For missions that can be accomplished using independent assets, either hull type is allowable. While it is true that ships have been designed and built up to 1500 feet in length compared to the longest semisubmersibles of less than 700 feet, the offshore industry does not consider the extension to up to the nominal 1,200-foot length to be a concern. Semi-submersible platforms seem inherently superior with respect to operational capabilities, with acquisition costs that are roughly comparable to an equivalently capable number of ships.
    - Missions that include CTOL operations definitely favor semisubmersibles.

- There is no penalty, and probable advantages, to choosing the semisubmersible hull, and operating them individually or connected if desired. On the other hand, choosing the ship hull type greatly complicates, and perhaps eliminates, CTOL runways and operations.

Relating the conclusion to the key air support requirement that drives platform length can refine this rather general statement.

- A vertical/short take off and landing (VSTOL) capable platform, nominally 1,200 feet in length, could be constructed today using either traditional ship hull technology, or by extrapolating semisubmersible technology beyond the present maximum of 660 feet.
- A C-130 capable CTOL platform could be constructed today with acceptable risk, nominally based on two to three connected modules, providing 2,500 to 3,000 feet of overall length.
- The full-capability, C-17-capable CTOL platform is considered feasible. This conclusion is based on the fact that no technology show-stoppers have been identified to-date, but is also tempered by the recognition that some critical design and analysis technology gaps are still pending completion due to limited S&T funds and program duration.

This Section has described the overall organizational and technical framework for the MOB S&T studies. The next four Sections highlight the objectives and major accomplishments for each product area. Note that each product area has two distinct subcategories.

2.2 Mission Requirements and Performance Measures

This product area was essential for two reasons:

- It supports the initial design of a MOB platform by deconstructing mission needs into quantifiable engineering design criteria (e.g., weight, volumes, runway size, etc.).
- It provides performance measures for rigorous evaluations of how well a conceptual (or in the future an as built) MOB platform satisfies given mission requirements for a site and season of interest.

Information from the first subcategory of studies provides an important common baseline of system capabilities for any subsequent design. Information from the second subcategory directly supports the program objective by providing quantitative performance measures. Example tasks included:

2.2.1 Deconstructing Mission Needs into MOB Design Criteria

This task first required the development of a rational, traceable methodology for extracting uniform physical design criteria (such as runway length, deployment speed, and cargo capacity) from an assumed mission set. The methodology includes the following steps:

- Identify multiple discreet missions from the MNS and other applicable documents.
- Develop mission concepts of operations (CONOPS) that describe operating environments, the MOB's role in plausible mission scenarios, and notional force list(s).
- Develop a system capability document (SCD) for each CONOPS that identifies specific MOB system capabilities required for executing the mission.
- Derive a performance requirements document (PRD) from the SCD, listing specific performance requirements for each system capability defined in the SCD.
- Derive specific physical requirements from the PRD for each mission, and assemble design

evaluation criteria (DEC) that satisfy all mission elements.

This methodology was applied to the MOB, based on a preliminary MNS that contained some unique logistical requirements for a floating structure, including:

- A runway length of up to two kilometers to handle U.S./foreign military and commercial logistical aircraft, including the C-17.
- Five million square feet of hangar/storage space (2.9 million climate-controlled).
- Self-propulsion for deployment and station-keeping.
- Air operations through Sea-State 6, cargo transfer through Sea-State 3, and survival in a 100-year storm.
- Commercial standards and commercial manning
- Command and control intelligence (C2I); command, control, communications, computer, and intelligence (C4I); selected depot maintenance; and selected combat and surveillance systems (such as Multiple Launch Rocket System and Tactical Missile System).

Of these requirements, the need to handle CTOL aircraft is the driving force behind module connectivity and MOB technical feasibility. The preliminary 1995 MOB MNS was deconstructed into four assumed missions that include all the specific MNS requirements within plausible scenarios.

The four assumed missions were identified as:

- ***Logistics Hub.*** A "hub and spoke" intermediate support facility for receiving, warehousing, and distributing equipment and supplies to sea, air, and land forces.
- ***Operational Maneuver From the Sea.*** A sea base for up to 20,000 marines, including facilities for assembly, staging, sea-based command, and indefinite support.
- ***Special Operating Forces.*** Support for Joint Special Operations Task Forces, including staging, logistical support, maintenance, and regeneration of combat units.
- ***Tactical Aviation Operations.*** Support for air operations initiated by other military assets (search and rescue, alternative landing, aircraft maintenance, stopover point, intelligence, and surveillance), but with no organic aircraft.

These four missions were deconstructed for the MOB, including additional studies to define key requirements, such as runway configuration, runway operating limits, and transit speed. Specific efforts either completed or in process include:

- ***Mission Deconstruction.*** CONOPS, SCDs, and PRDs were developed by Syntek. Whitney, Bradley and Brown, Inc., who also identified landing and take-off requirements for a variety of aircraft, prepared the Tactical Aviation CONOP.
- ***Hierarchical Database.*** Band, Lavis, and Associates, Inc. (BLA), developed a hierarchical database that documents the mission deconstruction process, providing traceability between design requirements and source documents. The database can be used to gauge the sensitivity of various physical requirements to changes in mission requirements. Syntek assisted with many of the entries in this database.
- ***Runway Requirements.*** The Naval Air Warfare Center-Aircraft Division, supported by the Army Corps of Engineers, defined fundamental air operation limits, such as allowable discontinuity at the joints between semisubmersibles, runway length and width limits, and environmental limits.
- ***Flight Deck Arrangement.*** Boeing developed an airfield layout based on civilian collision and safety requirements, such as those of the Federal Aviation Administration (FAA) and the

International Civil Aviation Organization (ICAO). Because width may be a major cost driver, the flight deck layout should be optimized to reduce width while still providing the necessary level of safety and accommodating the required transfer of cargo.

- ***Transit Speed Studies.*** Whitney, Bradley, and Brown, Inc., determined that a minimum MOB transit speed of approximately 12 knots is sufficient to meet the baseline mission requirements. (Note that MOB modules are expected to achieve speeds of 15 knots or greater using the available power designed into the dynamic positioning system.)
- ***Container Transfer Requirements.*** The National Institute of Standards and Technology (NIST) has undertaken tasks to define MOB container crane and cargo handling requirements and to assess the state of the art in motion-compensated cranes for moving containers from ship to MOB and MOB to lighter.

2.2.2 Performance Measuring Tools

A prototype set of physics-based performance assessment tools has been developed to quantify how well, and at what cost, a MOB concept performs a given mission. The S&T Program has emphasized objective, probability-based measures of performance, cost, and risk. When used properly, these tools can identify operational bottlenecks, compare concepts, and quantify the impact of changes in mission requirements. Key performance measures include:

- ***Operational Availability Model (Ao).*** This tool statistically quantifies performance measures such as the percentage of time the MOB can perform a given mission, or the effective cargo throughput rate for metocean conditions corresponding to a site and season of interest. The model considers the failure rate of key systems or components, the percentage of time lost to repairs or extreme weather at a designated location, and other factors that affect mission performance. Bechtel has developed and partially qualified a basic model suitable for most design concepts. However, the model has not been used for full formal analysis of any concept.
- ***Design Synthesis Model with Life-Cycle Costing.*** BLA adapted an existing design synthesis model (called PASS) from monohull, whole-ships to MOB semisubmersibles. This type of model uses an experience-based rule set to determine whether a given design provides reasonable geometry, weight, volume, and other parameters for the specified systems and performance characteristics. The PASS model checks completeness of design concepts and provides cost estimates.
- ***Ship Cargo Transfer Rate Model.*** McDermott Technologies, Inc. and Systems Modeling Inc. developed a discrete event simulation model to evaluate at-sea transfer rates of container and vehicular cargo between the MOB, Sealift ships, and lighters. Key factors include cargo handling equipment characteristics and relative wave-induced motions between the vessels. The simulation model is based on the McDermott MOB concept and the NIST Robo-crane, but it can be adapted to other designs, and the results can be transferred directly to the Ao model
- ***Construction Feasibility Assessment.*** The University of Maryland Center for Technology and Systems Management assessed the feasibility of MOB hull construction by evaluating the risks and costs of different construction strategies. Five design concepts were modeled for two construction scenarios, and cost estimates were made for hull construction only.

The mission requirements and performance measures part of the S&T program has contributed the following key advances toward the program goals of cost and feasibility:

- The mission deconstruction methodology has not only improved program direction for the MOB, but can be used as a process in other programs to sharpen focus, improve mission performance,

and reduce cost.

- The key design criteria of allowable runway misalignment and transit speed have been quantified. These numbers bear directly on the feasibility of all design concepts and were not available from the preliminary MNS.
- A number of performance measurement tools have been developed that will be instrumental in advancing MOB design if this program continues.
- The constructability study shows that the U.S. shipbuilding industrial base can build a MOB in a reasonable time frame and could probably support competitive bidding.

Descriptions of each of the specific S&T tasks for this product area are given in Appendix A.

2.3 Standards & Criteria

The Standards & Criteria [and the Design Tools] product areas work together to provide the three essential requirements of any *Classification Guide*:

- Design methodology,
- All necessary analysis and simulation models, and
- Validation of both.

The approach used for development of the *Guide* was to use engineering fundamentals to modify existing commercial standards to the unique characteristics of the MOB platform and military mission. The two subcategories in the Standards & Criteria product area were:

- Development of a preliminary *MOB Classification Guide* addressing hydrodynamic/ hydroelastic wave loads, survival and fatigue structural responses, stability, constructability, and stationkeeping. The emphasis was on platform integrity, as defined by a variety of fatigue, operating, and survival scenarios.
- Quantitative definition of: (1) realistic environmental descriptors for survival, operational, and fatigue analyses, including wind, waves, and current metocean descriptors, and (2) vulnerability criteria based on explosive events. Directional, temporal, spatial, and joint environmental probabilities were included based on a physics-based examination of known physical ocean processes (e.g., hurricanes). This information was incorporated into the *Guide* and used to provide for a realistic and consistent preliminary evaluation of all MOB configurations.

ONR contracted the American Bureau of Shipping (ABS) to lead the development of the *MOB Classification Guide* to serve as the basis for certifying the structural adequacy and safety of a MOB. Development and application of this *Guide* allowed ONR to identify key technology and information shortfalls critical to MOB feasibility. This approach required collaboration among the Marine and Navy operational communities, as well as the technical and acquisition communities of ONR, NAVSEA, NAVAIR, NAVFAC, ABS, academia, and industry. This collaborative approach among the users, industry, and ABS enabled the ONR S&T Program to deliver a very credible design capability comprised of validated tools and a *Classification Guide*.

This part of the S&T Program answers the fundamental question of *how should a MOB be designed and certified*. The classification societies have published standards for semisubmersibles based on theory and empirical evidence, and the U.S. Navy has its specifications, also based largely on experience. However, the size and configuration of an assembled mile-long MOB are unlike any ship ever built, and there is no experience base for estimating risk. This has required codification of a design process based on

fundamental engineering principles combined with careful risk management for each major element of the MOB system. The primary deliverable from this S&T Program product area is a design guide that includes the following:

- Environmental design criteria (wind, waves, and current)
- Initial survivability assessment and explosive safety (hostile action or accident)
- Stability
- Design methodology to convert mission, environmental, and survivability criteria into MOB loads
- A reliability-based structural design code (or standard) that relates MOB strength to the specified loads and standards of performance.

Although still incomplete, the *MOB Classification Guide* and accompanying *Commentary* are a road map for developing the preliminary and detail design of any MOB semisubmersible concept to meet any set of mission needs at a given probability level. It includes all subjects, such as dynamic positioning, life-cycle maintenance, and environmental compliance, that fall under certification and classification. The following sections describe progress to date and recommendations for completing this important document.

2.3.1 Environmental Design Criteria

The current state of the art in hydrodynamics-based ship design is to calculate or model test the response of a given hull form to a series of long-crested waves. The motion response of the hull form can then be predicted for any design sea state by linearly combining the responses for normalized long-crested waves in the correct proportions.

This prediction process is based on a number of basic assumptions:

- The waves are infinitely long (two-dimensional), or have a known directional spread.
- A two-dimensional wave, when placed in the right position, results in the worst-case loading for the ship structure. (Traditional "hogging/sagging" assumption.)
- The ship is infinitely rigid and does not deform under wave loading.
- The ship natural period of vibration is much shorter than the wave periods, preventing resonant or "ringing" responses.
- The hull form is small with respect to phenomena such as solitons and storm fronts. Subsequently, the corresponding dynamic loads do not exhibit a spatial variability over the hull and the motions are well-behaved.

All these assumptions are suspect for a structure the size and shape of a MOB. In particular, this S&T Program funded eight separate pioneering oceanographic investigations to evaluate wave characteristics at the one mile scale of the longest MOB platforms. The results are of direct benefit to the MOB and will be of great benefit to the design of other future very large floating structures, such as airports. The first study (led by Bechtel and supported by experts from academia and Government) developed a database of wind, wave, and current statistics for 20 years at 25 sites worldwide, representing probable MOB transit and operational sites. The study also included theoretical models to estimate variations in wind velocity and water particle velocity due to ocean fronts and soliton waves. Ultimately, these weather criteria need to be incorporated into the *Guide* on a reliability basis to support probability-based design goals.

Eight separate studies were initiated to evaluate wave coherence. Three studies, with investigators at

National Aeronautics and Space Administration (NASA), Johns-Hopkins/Applied Physics Laboratory, University of Wyoming, and ERIM International, were focused on the review and filtering of NASA scanning radar altimeter (SAR) data from Hurricane Bonnie and other storms to look for coherent wave crests of sufficient length to impact MOB. Two studies at Woods Hole and Washington State University used existing wave probes in Lake Ontario to measure and validate wave models of varying levels of coherence. The remaining three studies (Massachusetts Institute of Technology, University of Hawaii, and University of Torino in Italy) considered physics-based numerical models of wave fields that could be used in nonlinear time-domain MOB studies to evaluate extreme waves and other effects. While preliminary at best, the collective results show that waves could be short-crested or long-crested on a scale that will impact MOB on a worst-case basis. The probability and occurrence of extreme events (such as rogue waves) may be greater than originally thought.

2.3.2 Survivability and Explosive Safety Requirements

The need and ability to survive hostile threats has been an issue in concept design and MOB feasibility. Although past U.S. Navy policy has excluded Sealift, prepositioning, and other logistical support ships from combatant survivability requirements, the MOB is a special case due to the level of investment and the length of time spent in the theater of operations. A conventional Sealift ship will arrive, quickly unload its cargo, and leave, whereas, the MOB will stay on site for the full term of operations. The *Guide* contains a significant amount of unclassified descriptive material concerning weapons effects and explosive safety. However, classified design requirements will be placed in a separate threat assessment report, which will be adopted by reference in the *Guide*. Currently, Marine Corps preliminary mission requirements specify only a Survivability Level I capability, which is generally limited to underwater explosion. The following paragraphs discuss MOB susceptibility to these and other hostile actions and accidents.

- ***Underwater Explosion.*** This threat arises from torpedoes and mines, causing high-pressure waves that typically buckle and tear hull shell plating. A properly located explosion will "break the back" of a normal ship, reducing hull girder strength to a small fraction of that needed for even calm water. Semisubmersible hull forms are far more resistant to this type of attack, because localized pontoon buckling does not affect the deckhouse. Therefore, hull girder strength is reduced by only a small fraction. Most of the column and pontoon boundary tanks are used for ballast or fuel, so puncture may not change (or may even reduce) the level of submergence.
- ***High-Impact Shock.*** The shock wave generated by underwater explosions is carried through the hull structure and into equipment mounted to the hull. Shock requirements on combatants vary, depending on how critical the equipment is to the ship's mission. As a logistical support facility with little or no organic combat capability, the MOB's critical systems are limited to propulsion, damage control (fire-fighting, etc.), ventilation systems, and air operations support equipment. The sheer size and mass of the MOB will result in less severe requirements than for typical surface combatants.
- ***Air Blast and Fragmentation.*** The above-water portions of the MOB are subject to both above-water explosions (nuclear, fuel/air, other) and fragments (small-caliber weapons, explosion fragments, etc.). Resistance can be provided by adding structure around the periphery, adding composite or metallic armor, and by shielding critical spaces within non-critical volumes. Significant, and possibly sufficient, protection can be obtained by the proper arrangement of magazines within topside spaces.
- ***Explosive Safety.*** The MOB will store aircraft and ground equipment (bombs, missiles, rockets,

shells, bullets) munitions that can detonate from fire, shock, and hostile action. Logistical assets typically have no resistance to internal explosions, and combatants cannot typically operate after or survive a magazine explosion. However, the MOB's size and arrangement have the potential for meeting land-based explosive safety requirements through a combination of physical separation, non-propagation walls, and the venting of explosive pressures downward through the deckhouse shell. NSWC-CD Code 674 and NFESC Code 62 have worked with ABS to provide non-confidential assessments of primary detonation damage in the Guide.

Survivability appears to be a non-issue unless more stringent mission requirements are invoked, at least compared to the current practice for combatants. The S&T Program has taken the necessary first step of a threat assessment study as a baseline for a systematic survivability analysis based on more specific (future) mission definitions. A decision will be required on the severity of the threat environment, with minor implications for weight, arrangement, and cost. An expanded discussion is provided in Appendix B.

2.3.3 Design Methodology

The *Guide* outlines the necessary procedures for converting design criteria into structural load conditions. Design criteria include environmental (wind, waves, current, etc.); mission (speed, payload, maneuvering, etc.); survivability (shock, blast, fragmentation, etc.); and inherent (stability, deadweight, hydrostatic) criteria. Past practice in ship design has featured benchmark load cases, based on a superposition of static loading and wave-induced loads for worst-case cargo arrangements. The wave-induced loads are based on conservative estimates of the ship's operating sea state (typically North Atlantic). Structural design rules are generally prescriptive, based on uniform working stress limits. Because there is no empirical database for structures the size of the MOB, it was necessary to develop a design methodology based on engineering fundamentals. The *Guide* defines the necessary process that a designer must follow to calculate loads, to meet prescribed partial safety factors, and to calculate probabilities of failure to compare with prescribed limits. The process permits differing levels of engineering complexity (quasi-static, frequency-domain based, hydrodynamic analysis and time-domain based, non-linear, hydrodynamic analysis) with appropriate levels of uncertainty and partial safety factors to achieve the overall reliability goals. At the start of the S&T Program, it was generally recognized that existing hydrodynamic tools were not able to analyze the MOB in its connected state, and that these tools needed improvement to reduce structural design risk. Otherwise, the required factors of safety would drive structural sizes (particularly connectors) beyond economic feasibility.

2.3.4 Reliability-Based Structural Design Code

The *Guide* was developed under guidance of the Standards and Criteria Working Group and is consistent with DoD acquisition reform initiatives regarding the use of best commercial practice. It is compatible with, and builds on, current U.S. Navy 6.3 (Advance Development) and 6.4 (Engineering Development) efforts in structural reliability, as well as the commercial adaptation of reliability-based structural design and life-cycle management.

Technologically, the reliability approach provides a systematic and logical process for quantifying the uncertainties in the design of an engineering system, resulting in more consistent design decisions. Engineering designs, such as the MOB are developed under conditions of uncertainty and involve some probability of failure or nonperformance. To ensure a high-performance reliability of the MOB as a system, the *Guide* is a reliability-based design rule that assigns system and subsystem lifetime target

reliability levels for key limit states (operational, fatigue, strength, survivability) that are consistent with the required probability of mission performance.

The development of the *Guide* has included two reliability-based design approaches suitable for preliminary and detail design. The load and resistance factor design (LRFD) approach is more appropriate for concept and preliminary designs when detailed hydrodynamic and finite element analysis studies are premature. LRFD is a better approach than conventional working stress, because it allows the application of partial factors of safety to suit the uncertainty of different design loads. The *Guide* also includes the requirements when a direct reliability analysis is required, where the uncertainties associated with design criteria, loads, calculation procedures, material, and construction processes are all quantified and combined to meet the reliability targets.

The *Guide* is the key integration and summary document for the S&T Program, documenting key design criteria, target reliabilities, design methodology, and requirements for structure and stability. It is a working document and, as such, should be updated to incorporate results from any continuing S&T Program work.

Descriptions of each of the specific S&T tasks for this product area are given in Appendix B.

2.4 Design Tools

The two subcategories in this product area were to:

- Advance seakeeping models, and
- Generate a comprehensive experimental data set for validation of the models.

This Program area focused on the development and validation of design tools in two areas: stability and hydrodynamics. Stability calculations measure a marine structure's resistance to turning over, or "capsizing." Hydrodynamics is the science of calculating the loads applied to a marine structure by waves, currents, and related ocean phenomena.

The primary motivation driving all of the advancements in this product area was the high uncertainty in estimated connector loads for the multiple-module platform concepts. Secondary motivations were to accurately quantify the wave field under and adjacent to a MOB platform because of its effect on cargo transfer operations and to understand the in-transit behavior of MOB modules.

The following sections describe progress to date. Details are provided in Appendix C.

2.4.1 Transit Stability of Semisubmersibles

When transiting, semisubmersibles are deballasted until the tops of the pontoons are just above the water's surface. This adversely raises the center of gravity and decreases stability, but the increased water plane area from the pontoons improves stability and the increased air gap reduces the risk of wave slamming on the underside of the deck structure. However, because the pontoon tops are nearly awash, the available righting energy is limited. Professor Falzarano at the University of New Orleans is developing the "phase-plane" method of dynamic stability calculation and assessment.

In a related effort, Professor Kriebel at the United States Naval Academy (USNA) is leading a validation model test effort by towing a single semisubmersible at speed. The USNA model is stiffer than, but geometrically similar to, the hydroelastic modules being tested at Carderock. The USNA model was used to investigate nonlinear wave response effects, such as air gap, the distance between the water's surface

and the bottom of the semisubmersible deckhouse.

2.4.2 Hydrodynamic Models

Accurate hydrodynamic analysis is required to minimize the uncertainty in estimated MOB module motions and connector loads and to characterize the wave field under and adjacent to a MOB platform because of the impact on cargo transfer operations and the air gap in extreme storms. Efforts were focused on developing, improving, and validating preliminary and detailed design hydrodynamic codes, including the ability to couple hydrodynamic results with structural finite element models. Contracted efforts included:

- ***Existing Program Baseline.*** Bechtel National was tasked to review and exercise commercially available programs for analysis of both unconnected and connected MOB modules. They found that all the codes reviewed provided generally equal results for a given MOB module, but that connector load prediction became unreliable for MOB configurations consisting of more than two connected modules. This study provides guidance on the proper methods for using these computer programs.
- ***Preliminary Design.*** (1) Dr. Chakrabarti at Offshore Structural Analysis developed a simplified hydrodynamic code that analyzes single body motions within a wave field, and then joins the results, using a scattering technique to analyze the fully coupled motions of a connected MOB. His program runs efficiently on a personal computer and, if validated, would be useful for parametric analysis during preliminary design. (2) Prof. Riggs at the University of Hawaii developed a user-friendly graphical interface for the MOB, using the HYDRAN diffraction code. The resulting program again employs a number of assumptions that makes it more useful for preliminary design, when the designer wants to consider the effect of parameters, such as connector stiffness, entrained water, damping, and column shape.
- ***Improved Frequency-Domain Diffraction Codes.*** The MIT-based WAMIT consortium modified both their linear diffraction code WAMIT and their higher-order panel code HIPAN to run faster and handle larger models, using a fast-Fourier-transform (FFT) acceleration algorithm. Recently, WAMIT Inc. announced that it was offering a new version of WAMIT with higher-order panels.
- ***Improved Time-Domain Nonlinear Diffraction Codes.*** Science Applications International Corporation (SAIC) has improved its time-domain code LAMP and is evaluating nonlinear effects, such as air gap and wave run-up. The MIT/WAMIT consortium has advanced their time-domain code AEGIR, using higher-order panels and the FFT accelerated solver, but this program is still in a preliminary stage of development and further work is required before it can be applied to practical problems with prescribed incident waves. The USNA model testing will provide validation data for this hydrodynamic work.
- ***Docking Model.*** C.J. Garrison and Associates developed a piece-wise stationary model for estimating wave-induced dynamics for the semisubmersible modules during connection and disassembly (SAIC's LAMP code is able to perform the same work, using a more computationally intense procedure).
- ***Integrated Frequency-Domain Hydrodynamics Model with Time-Domain Structural Model.*** McDermott Technology, Inc., with consultation from MIT and AeroHydro is working to integrate a HIPAN, frequency-domain, hydrodynamics model with a time-domain, ABAQUS, structural, finite element analysis, using surface-mapping algorithms written by AeroHydro. The intent is to perform an coupled connector/structure analysis for the MOB in a defined sea state.

2.4.3 Validation Testing

Three sets of laboratory-scale experiments were conducted to provide specific data for model validation.

- ***Hydroelastic Model Test***. The most extensive model experiments reproduced the motions and connector loads on a hydroelastic MOB platform in waves. A 1:60 scale generic MOB platform architecture was used consisting of four semisubmersibles connected by pairs of stiff but elastic 3-axis cantilevers. The elasticity of the semisubmersible test modules themselves was carefully designed and constructed with the same resonant characteristics of the full scale modules, but with elasticity deliberately reduced to amplify the difficult-to-measure small model scale response. One module and two connected module tests were also conducted. Measurements included motions, connector forces, and the wave field for harmonic and irregular waves. These hydroelastic tests were conducted at the Naval Surface Warfare Center Carderock Division.
- ***Transit Stability Tests***. The objective of this second set of tests was to measure wave-induced dynamics of a single semisubmersible at the deballasted draft, at zero and finite forward speed. This reproduces conditions associated with transit from one theater to another while the semisubmersible is riding with the pontoons at the surface. These tests were conducted in the towing tank at the U.S. Naval Academy (USNA) using a single, rigid 1:70 scale semisubmersible module. That data is being analyzed at the University of New Orleans.
- ***Air Gap Model Tests***. The objective of the third set of tests was to measure the zero-speed wave amplification under the MOB. This is a critical concern because of the numerous types of large and small vessels involved with sea-based cargo transfer, and the need to avoid wave impact loads on the upper deck structure in storms. These tests were also conducted in the towing tank at the USNA using a single, rigid semisubmersible module. SAIC, Annapolis, analyzed this data.

Descriptions of each of the specific S&T tasks for this product area are given in Appendix C.

2.5 Alternative Concepts

The two subcategories of this product area were to:

- Examine representative preliminary *system* concepts (point designs) of the longest platform to identify their respective advantages and limits, and
- Examine and advance *subsystems and components* critical to MOB system concept feasibility.

In the first subcategory, four system concepts were developed through the preliminary design stage. Three of the concepts were advanced representing differing connection schemes, while the fourth explored the use of reinforced concrete as an alternative to an all-steel hull. These concepts are contrasted in Figure 2.

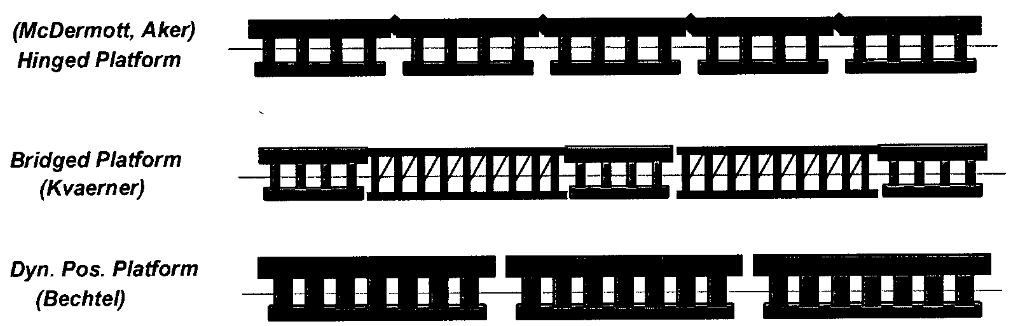

Figure 2. MOB Candidate Architectures for Full CTOL Platform

A limited number of parametric studies were also completed to investigate some platform design parameters such as number of modules, module hull type, and connector characteristics.

The four conceptual architectures are more fully described on the following pages.

- ***Hinged Semi-submersible Modules.*** The McDermott concept features five, 300-meter-long, steel semisubmersibles, connected at the deckhouse level to form a 1500-meter-long runway. The arrangement is shown in Figure 3. Module connection is made with a centerline ball joint, combined with preloaded, nonlinear, compliant connectors (port and starboard). Each semisubmersible has its own dynamic positioning system of eight rotating thrusters for station-keeping and individual deployment.

  McDermott conducted extensive and unique analysis to understand the relationship between connector compliance, module flexibility, and global motions and connector load. In addition they devised a wide range of load reduction strategies and connection options that reduce connector load but at the expense of increased relative motion between modules. According to the industry review team, the current compliant connector method is much less risky than the piano-hinge system proposed by McDermott in 1995. The industry review team also concluded that this methodology is feasible within the current industry state of practice. However, special flight deck runway bridges are required to telescope between modules during these relative motions. While the industry experts concur that these connection schemes are feasible, the size of the connectors is beyond industry experience. Confirmation of feasibility depends upon the validation of the hydrodynamic models and subsequent testing of these connector schemes at suitable scale.

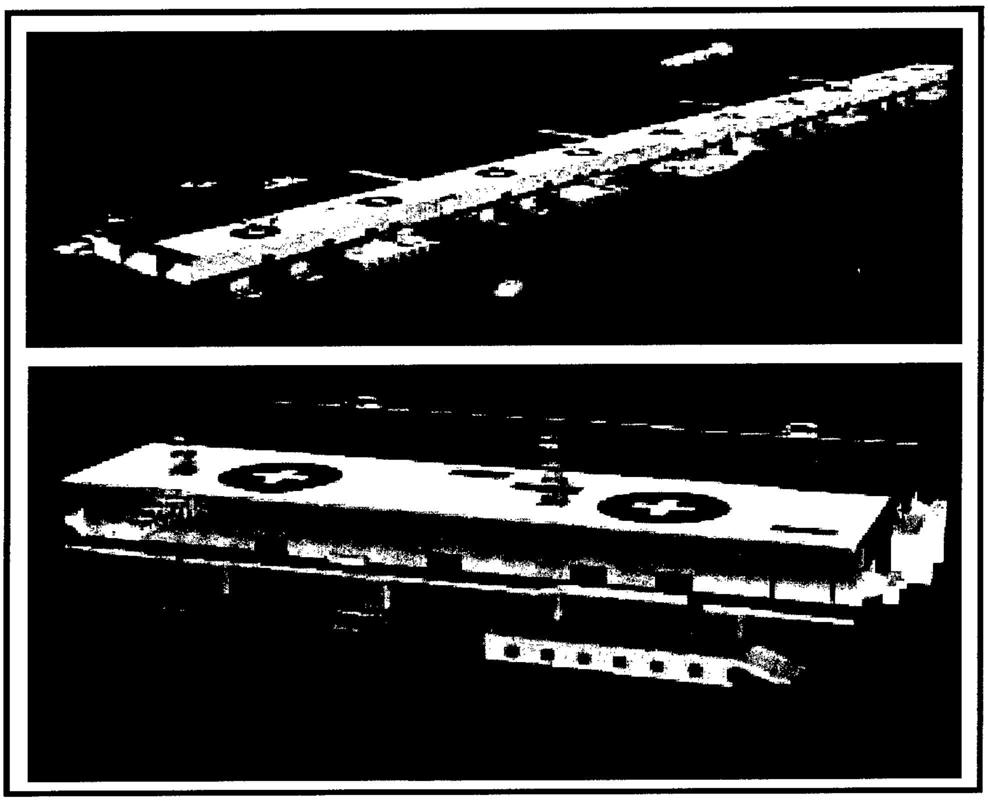

Figure 3. McDermott MOB Concept.

- ***Semi-submersible Modules with Flexible Bridges.*** The Seabase consortium of Kvaerner Maritime (Norway) and Boeing developed this concept. It features three 258-meter-long, steel semisubmersibles, connected by 430-meter-long, flexible bridges to form a 1,500-meter runway (Figure 4). The flexible bridges have the minimum hull girder torsional and bending rigidity necessary for transit. They are rigidly connected to the semisubmersibles, but flex between the connectors to provide smooth gradual deflections in the runway. The flexible bridge truss includes damping elements to mitigate resonance. The bridges are ballasted down onto keyed connections on the semisubmersibles at the deck and pontoon levels. The connection between semisubmersible and bridge is rigid and continuous across the entire module width. There are some technical problems to be resolved, including bridge transit speed, damping element reliability (particularly underwater), and bridge truss fatigue in higher sea states.

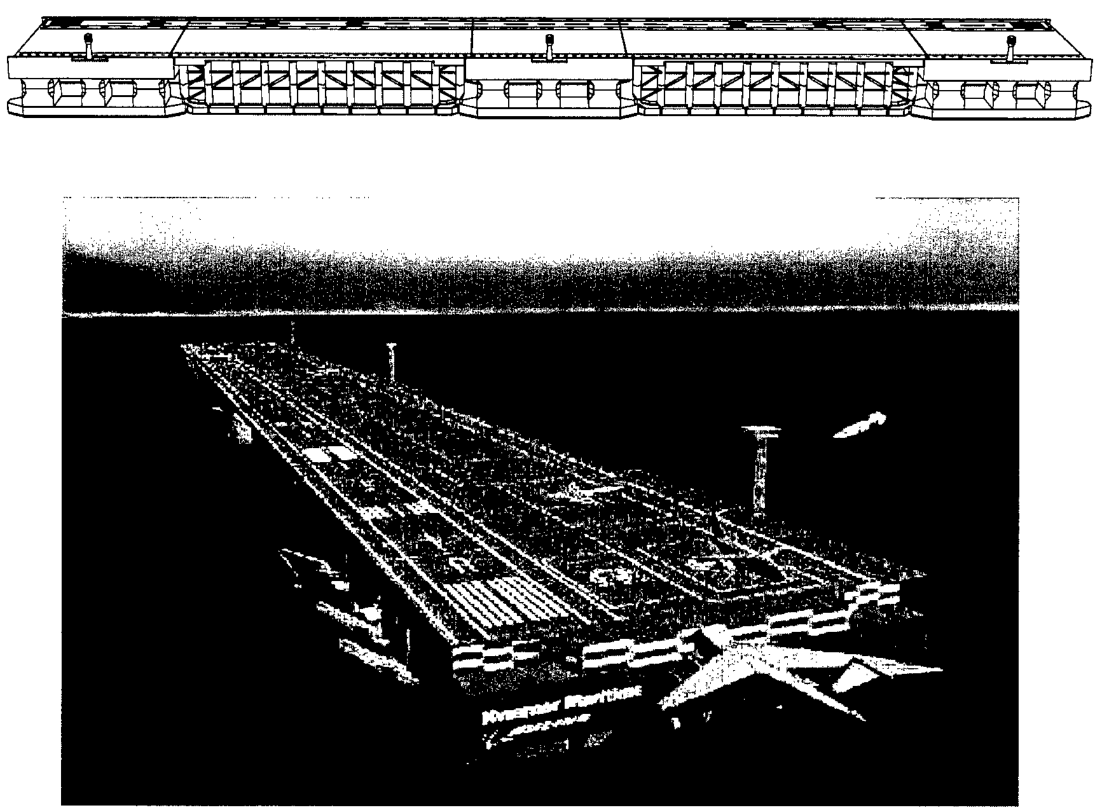

Figure 4. Kvaerner MOB Concept.

- ***Independent Semi-submersible Modules.*** This concept proposed by Bechtel National includes three semi-submersible steel modules, each about 1600 ft (488m) long, that are not structurally connected but instead rely on dynamic positioning to maintain overall orientation and relative position between modules (Figure 5). A drawbridge will span the gap and create a continuous airplane runway but these bridges do not take connection loads. The Bechtel design trades dynamic positioning risk for connector risk. All design concepts require a powerful, complex DP system for stationkeeping and docking, but the Bechtel concept also requires fault-tolerant DP for maintaining runway alignment. The design of the runway connection bridges is complex because relative module motions are unrestrained by connectors. Bechtel developed a cargo transfer bridge that spanned between modules and optional low-force connectors to improve reliability and save fuel in low and moderate sea states.

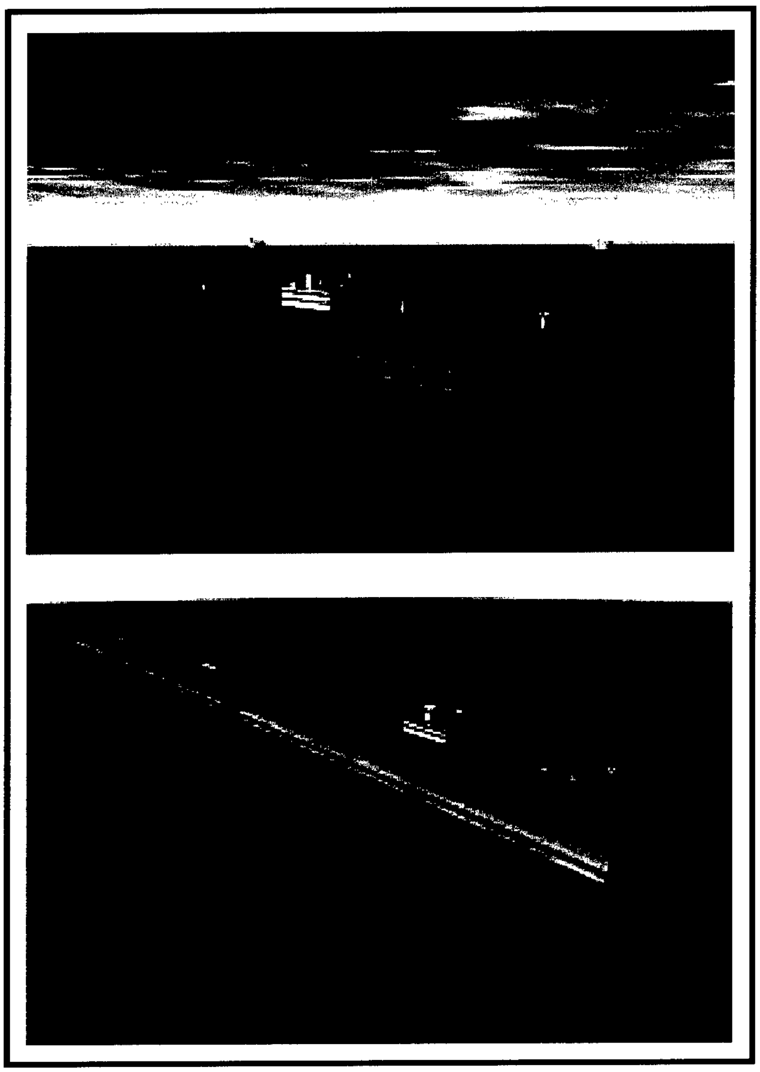

Figure 5. Bechtel MOB Concept.

* ***Concrete Semi-submersible Modules.*** The Aker Maritime (Texas and Norway) concept consists of four 380-meter-long semisubmersibles connected at the deck level using elastomeric connectors. The center connector resists longitudinal and lateral relative motions, and the port and starboard connectors resist vertical motions (therefore, relative roll). This design features a steel deck structure mounted on a post-tensioned concrete semisubmersible hull (Figure 6). The use of concrete offers advantages over steel in terms of life-cycle cost, corrosion, and fatigue. However, there are questions about performance of concrete in the presence of underwater explosion, particularly at the column/pontoon joints. The Aker concept has connector and runway bridge issues similar to those of the McDermott concept. Aker has a proven ability in concrete design from projects such as Troll and the Gullfaks-C gravity-based platform, similar in scale to the MOB.

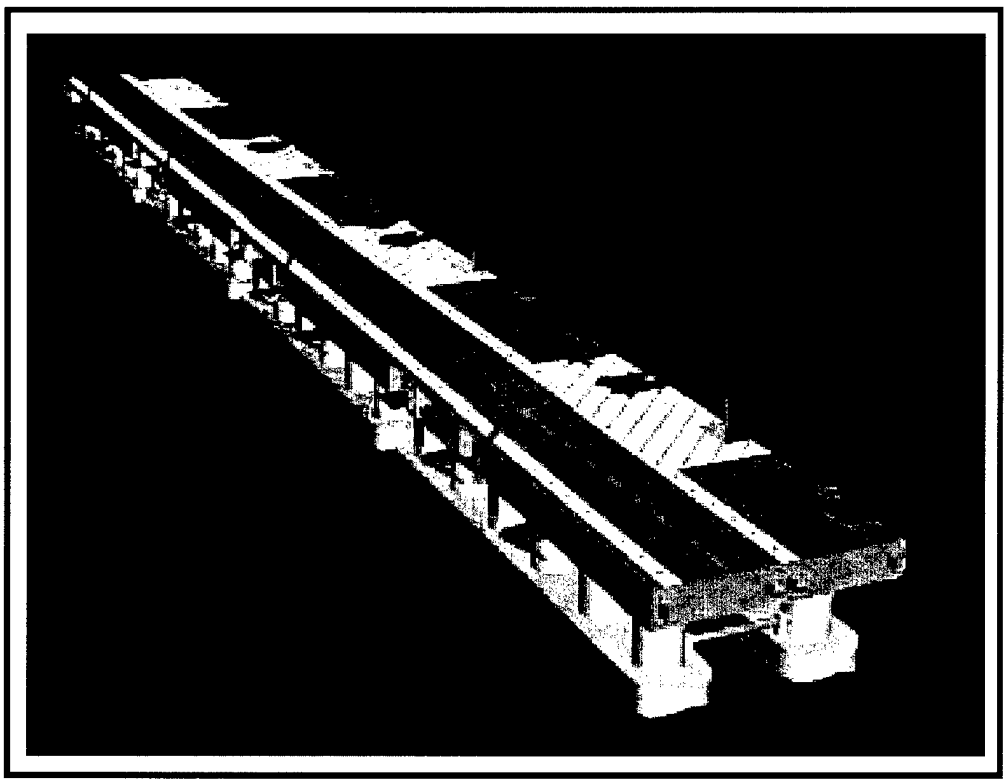

Figure 6. Aker MOB Concept.

MOB components advanced in the second subcategory of this product area included:

- Inter-module connectors,
- Alternative marine materials,
- Station-keeping sub-concepts (mooring and dynamic positioning),
- Response mitigation methods,
- Construction and repair methods, and
- Open-sea cargo transfer techniques.

Descriptions of each of the specific S&T tasks for this product area are given in Appendix D.

2.6 Program Schedule

Initial funding to develop a Technical Program Plan was released to ONR in September 1996. Funding to begin execution of this program was released to ONR in February 1997 ($16M) and August 1997 ($9M). Congressional plus-ups in FY98 ($5M released to ONR in June 1998) and FY99 ($4M released to ONR in June 1999) have allowed work to be initiated on many of risk areas identified after the start of the program.

The schedule for executing the various elements of the MOB program is shown in Figure 7 below.

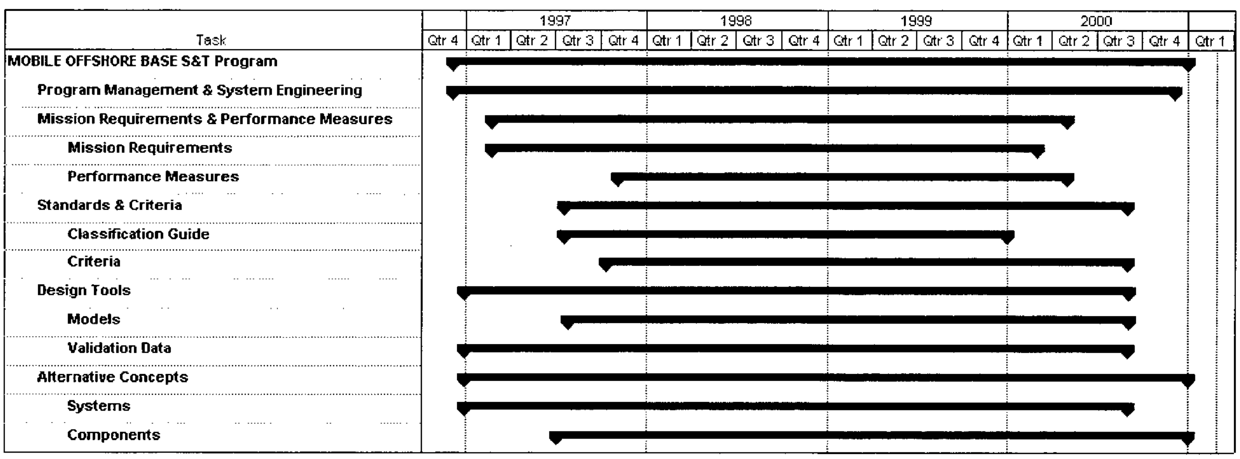

Figure 7. MOB S&T Program Schedule

2.7 Major Program Deliverables and Accomplishments

Major accomplishments from the MOB S&T program are summarized in Table 2. A more detailed discussion and listing of all accomplishments are presented in Appendices A-D.

Table 2. Summary of Major Accomplishments.

Technology Area	Deliverable
MOB *Classification Guide* (Draft) and accompanying *Commentary*	• Design standard addressing MOB structural adequacy and safety • Design criteria including metocean environmental specification as well as survival and fatigue factors • Operational vulnerability design guidelines
Concepts of Operations (CONOPS) and Functional Requirements	• Five mission-driven CONOPS • Development and validation of system design requirements derivation model (e.g., platform size, personnel requirements, and cargo throughput model) • Development of draft requirements for air operations
MOB Performance Models	• Adequacy of platform capacity versus functional requirements (PASS model) • Operational Availability model for evaluation of platform performance versus configuration and site descriptions • Risk-based tool to evaluate module construction feasibility • Cargo transfer rate model
Improved Hydrodynamic and Hydroelastic Models	• Next generation modeling capabilities in the frequency domain for hydrodynamics and hydroelastics of articulated MOB platforms, including advancements and/or development of – HIPAN (WAMIT) – OSA (shell) model – HYDROMOB • Time domain hydrodynamic models – LAMP – MOB-DYNSIM • Hydroelastic laboratory validation tests of 1-, 2-, and 4-module connected platforms at 1/60 scale • Transit draft and air gap laboratory validation tests at

	1/70 scale • Developed mesh-independent universal interface between hydrodynamics and structural numerical models (HYLOADS)
MOB Conceptual Design	• Semisubmersible modules with complaint connectors • Semisubmersible modules with flexible bridges • Independent Semisubmersible modules • Reinforced Concrete lower hull (columns and pontoons)
Critical MOB Subsystems	• Assessment of Connector Technology (survey of existing FPSO hardware) • Assessment of Cargo Transfer Technology (NIST) • Advancement of Dynamic Positioning Technology (control system review completed; laboratory demonstration tests ongoing through Fall 2000) • Evaluation of Reinforced Concrete • Development and Validation of Suction Pile Anchor (Mooring) model • Compliant Connectors: Concept Studies

2.8 Quality Assurance (QA)

The unprecedented nature of a MOB, along with the wide spectrum of inter-related technologies, made it prudent for this S&T program to institute a comprehensive QA program. This enhanced the reliability and accuracy of all program products, reduced the probability that key technology issues were missed, and ultimately enhanced the safety and operational effectiveness of a MOB. Several QA mechanisms were used:

Technical Reviews. Government representatives conducted on-site contractor progress reviews on at least a quarterly basis to monitor progress and resolve any pending problems. An important aspect of these meetings was that the contractors were required to submit a general agenda and any relevant draft deliverables prior to the meeting to allow for meaningful government and consultant preparations prior to the meeting. An equally important function regarding technical reviews was that drafts of all reports were thoroughly reviewed by a panel of government and outside experts prior to finalization.

Independent Reviewers. Additional expertise was provided by an independent team of outside technical experts, who semiannually reviewed the overall program content for consistency and to insure that the program made best use of all pertinent technology. This primarily academic expertise was complemented with experts from several government agencies where appropriate (e.g., for military air operations and survivability criteria). These experts participated in the working group and semi-annual meetings. These experts were also available for direct consultations to program contractors.

Name	Expertise	Affiliation
Dr. Al Ang	Structural Reliability	A.H-S. Ang and Associates; University of California, Irvine
Dr. Max Cheung	Ship Structures	MCA Engineers, Inc.
Dr. Jim Garrison	Numerical Hydrodynamics	C.J. Garrison & Associates; Oregon State University
Dr. Joe Penzien	Structural Dynamics	Int'l Civil Engineering Consultants, Inc.; University of California, Berkeley (Prof. Emeritus)
Prof. Marshall Tulin	Theoretical Hydrodynamics	Director, Ocean Engineering Laboratory, University of California, Santa Barbara (Prof. Emeritus)

Working Groups. The task for these groups was to facilitate the exchange of information among contractors and government within specific technical areas. Working group type and membership varied during this program and were active on an as-needed basis. For example, the initial working groups included mission requirements and performance measures, standards and criteria (focus on *Classification Guide*), connectors, and design tools. New groups were added including wave coherence, dynamic positioning, and hydroelastic testing. Membership in these groups consisted primarily of representatives from each of the participating contractors who, because they were practitioners in the field, brought a valuable balance of technology and industry practice expertise to optimize the value of deliverables in each product area. Additional members included other government and independent reviewers. These groups focused on the practical implementation of technology for MOB, and were headed by the government leader for each respective product area. Working group memberships are listed in each of the respective Appendices.

3 MOB FEASIBILITY AND COST

This section addresses the Program objective of estimating cost and feasibility for MOB. The first subsection addresses feasibility. The issues of acquisition and life cycle cost are addressed in the second subsection.

3.1 Feasibility

The following framework was used to evaluate the feasibility of these innovative structures:

- A *necessary* characteristic for declaring feasibility of a candidate platform was that it be survivable to all natural and hostile threats. This did not necessarily require that the platform remain fully intact, but rather not fail; as an example, a connected platform could suffer irreversible damage to connectors during a storm, but pass this criterion because the modules did not sink.
- A *desirable* characteristic for declaring feasibility was that the candidate platform accomplish all of the mission requirements – in other words, be fully functional.
- Finally, it was recognized that a number of feasibility assessments would be necessary, reflecting the fact that:
  - there was a number of candidate missions, with a minimum platform nominal length of 1,000 feet and a maximum of 6,000 feet, and
  - each conceptual MOB platform architecture had unique advantages and possible design limits.

Assessing feasibility was necessarily subjective, given the undefined MOB mission(s), the (consensus opinion) fact that MOB technology was not sufficient at the Program inception to reliably design a platform, and the fact that this S&T Program did not advance platform designs beyond the preliminary design stage. The following process was used to assess feasibility within the framework of those conditions:

- Nominal platform dimensions were obtained by deconstructing representative MOB missions into associated design criteria. Supplemental studies provided supporting operational requirements such as cargo throughput, transit speed, and general utility.
- A reliability-based design procedure based on fundamentals was developed to ensure structural reliability and stability for these innovative structures, including a preliminary metocean (wind, waves, current) specification at the unprecedented scale of the longest MOB platform. Hydrodynamic analysis tools were developed or improved to a degree sufficient for MOB design.
- Four candidate connection schemes were advanced through preliminary platform studies. All four platform concepts feature different advantages and design challenges. Viable construction procedures were advanced and were concluded to be within the capabilities of the shipbuilding industry.

The Program's feasibility conclusions are considered reliable, based largely on a second consensus conclusion at the conclusion of this S&T Program, that all of the key technology issues that put MOB beyond the state-of-practice had been either resolved or evaluated sufficiently to conclude there were no inherent showstoppers.

The two feasibility criteria of survivability and functionality are assessed separately below.

3.1.1 Survivability

The survivability assessment for a structure as unprecedented as the full MOB multiple-module platform was complicated by three factors.

1. The first was the *uncertainty in the threats* as described in Appendix B. Consider survivability to natural phenomena such as typhoons and hurricanes. The offshore community has yet to develop a satisfactory description for such storms at the scale of existing offshore facilities, and the larger unprecedented length of the longest MOB platforms acts to further amplify that uncertainty. There is also uncertainty in survivability to explosive threats (often referred to as "vulnerability") which addresses direct damage from external threats as well as indirect damage from accidental detonations. Neither the set of weapons appropriate for an asset such as MOB nor the required level of construction relative to damage control were defined during this S&T Program.

2. The second factor was that there was only limited experience with connected floating structures, and that introduced *uncertainty in the expected failure modes* of a MOB response. A dramatic illustration of this was the realization that the longest MOB semisubmersible platforms were highly sensitive to torquing induced by near beam-on incident waves; this was wholly unanticipated prior to completion of the first dynamic response studies at the Program inception. The *MOB Classification Guide* will define criteria for both of these first two topics when it is completed.

3. Third, this S&T Program only sponsored platform studies up through *preliminary design*. Survivability is typically addressed parametrically by investigating design details such as bulkhead construction alternatives, and such studies are more appropriate to later design stages. For example, while the Navy has extensive experience with the behavior and design of displacement monohulls to such events, the response of semisubmersible hull forms (or connected platforms) has never been evaluated. (For example, what are appropriate damage criteria to define for the hull and presumed associated maximum sea state?)

3.1.2 Functionality

The second characteristic for assessing feasibility was that the candidate platform be capable of accomplishing the mission requirements, i.e., provide a particular service using given assets (aircraft or vessel) under specified metocean conditions. Assessing functionality was difficult for several reasons:

- There were no official missions, only representative missions (and associated required services) defined by this Program for illustrative purposes.
- Platform particulars were not addressed in the preliminary designs, and this made quantitative assessments impossible. For example, while a runway and parking/unloading area are necessary for air operations, a third "taxiway" would further increase throughput. But it is not yet possible to design a corresponding platform because definitive requirements and dimensions for safe air operations have yet to be established (see Appendix A).
- The tools needed to assess functionality, specifically the Operational Availability and Cargo Transfer models described in Appendix A and the hydrodynamic tools described in Appendix C, were developed during the course of this S&T Program and were therefore not available to the system designers.

3.1.3 Summary of MOB Feasibility

Assessing MOB feasibility was difficult for the reasons given above. However, a limited number of representative studies were completed, and from them it is possible to make the following preliminary conclusions:

1. Consider first the individual MOB semisubmersible modules (which can satisfy many missions). Undamaged modules would definitely be survivable in storms. The survivability of individual, damaged MOB semisubmersibles has not been formally assessed but is presumed, based on nominal damage scenarios and the assumption that any damage around the waterline would have a minimal impact because the columns already contain a significant amount of ballast water. And while the modules could be twice as long as existing semisubmersibles, appropriate fabrication techniques and sites were identified. These two conclusions lead to the first feasibility conclusion:

MOB semisubmersibles up to 1,200 and perhaps longer are considered buildable today.

2. The next logical category of platform to assess has additional length to accommodate conventional fixed wing aircraft (e.g., C-130) for local, in-theater operations. For such platforms it appears to be feasible to design and build connectors of sufficient capacity for platforms comprised of two or three connected semisubmersible modules. Thus,

MOB platforms up to 2,500 – 3,000 feet consisting of between one and three modules are considered feasible.

3. There are two scenarios regarding the survivability of the longest MOB platforms to extreme storms – for disconnected and connected architectures. Disconnected modules can survive storms as concluded above, and that is the presently presumed course of action for storms. On the other hand there are significant operational benefits and reduced risks associated with architectures that can stay connected during storms. However, the survivability of connected architectures has not yet been satisfactorily demonstrated, although one limited study showed that it appeared possible to design compliant connectors for the McDermott platform to allow it to survive in a connected state in 50-foot significant seas from the bow. These longest MOB platforms are very stable, with vast internal volume, and are therefore projected to be fully functional. This lead to two feasibility conclusions regarding these most capable MOB platforms:

6,000 foot long platforms are feasible, pending completion of the remaining S&T described in Section 3.6.

And

All of the platform architectures (compliant, bridged, independent, and concrete) are still viable candidates.

3.2 Cost Estimates

The second Program objective was to estimate cost. At the beginning of the S&T program, there were a number of questions associated with the construction of such a large structure in the United States, including:

- *How many different platform configurations should be considered, and what are the advantages and limitations of each?*
- *How difficult will it be to construct the individual semisubmersible modules?* (The present system

designs resulted in modules ranging from 858 to 1590 feet (258 to 485 meters.)

- *Are there any inherent scaling problems in manufacturing components (such as connectors and dynamic positioning thrusters) at the expected larger sizes?*

Only approximate answers can be given to these questions at this time. Hence, all of the cost estimates from this Program are at best a rough order of magnitude (ROM) for several reasons:

- Basic platform dimensions are still undefined. Hence, a baseline 5,000-foot long MOB logistics platform was arbitrarily chosen (with uncertainty as to the required beam, internal volume, necessary horsepower in thrusters, etc.). Also, the cost was defined as the hull and basic machinery, excluding military hardware.
- The level of construction is undefined with respect to vulnerability (i.e., combatant versus auxiliary).
- The economy of scale versus the number of units to be purchased, the required timeline, and/or domestic versus foreign sourcing is unknown.
- Only preliminary designs were completed that did not allow for any systematic investigation of cost reduction measures for either the basic platform design, components, life-cycle inspection and maintenance, etc.
- All of the above, plus uncertainties over the intended utilization of a MOB over its life (percent of time laid-up, training, or operating, and at what sites) made life cycle costs too vague to address at this time.

Three independent sources were used to estimate acquisition costs subject to these conditions:

- Four system designer estimates
- PASS model cost estimates
- University of Maryland (UM) construction cost estimates

Further details are presented in Appendix A. Representative observations are:

- All of the proposed MOB semisubmersibles are larger than any existing semisubmersible. However, fixed structures of comparable size have been built, and the techniques for offshore assembly of major fabricated assemblies into finished platforms have been demonstrated in commercial applications.
- A risk-based constructability analysis conducted at the University of Maryland (UM) showed that MOB modules could be built in the U.S. using onshore and afloat facilities. Aker has proposed a dedicated onshore facility capable of building complete modules.
- The UM study estimates a work force of 16,000 to 30,000 people for an 8-year period to build enough MOB modules to form a 5,000-foot CTOL runway. At this level of effort, it should be possible to solicit two credible, competitive bids from the existing U.S. shipbuilding industry.

3.2.1 Summary of MOB Cost Estimates

An independent group of marine engineering experts from industry, the American Bureau of Shipping, and academia was tasked to review the ONR MOB Program and its products and render an opinion on MOB feasibility and cost. The resulting assessment report was provided to Congress in April 2000 (Cheung and Slaughter, 1999). That study concluded the following.

The cost of a single 1000-1200 foot MOB (semisubmersible) module is estimated at approximately $1.5 billion for the hull and basic machinery only.

This is considered quite comparable to costs estimated for more conventional monohull logistics ships presently being considered for Navy acquisitions.

Regarding the 5,000-foot long CTOL capable MOB, the four concept designers provided construction cost estimates ranging between $5 billion and $10 billion. Recall that these four platform designs are quite different, and that some of those estimates included design and facilities costs. Estimates from the PASS model (based on historical trends for semisubmersible construction) ranged from $6.0 billion to $7.4 billion. Cost estimates made by the University of Maryland ranged from $3.8 billion to $5.3 billion for hull construction only.

Based on this information and general experience, a bare-bones, 5,000-foot MOB is likely to cost not less than $4 billion nor more than $8 billion.

Note that the cost of a single MOB semisubmersible module is in fact quite comparable to other, more conventional, proposed, displacement hull designs (e.g., LHA). Also, the use of a MOB would avoid nonrecoverable costs associated with building and abandoning temporary land bases such as Somaiia and Bosnia. It is also pointed out that the rapid response possible with relocating a "ready-to-use" MOB versus the time required to construct or upgrade new, temporary terrestrial facilities has added military value that is difficult to quantify.

Additional information regarding feasibility and cost is available in "The MOB S&T Program: An Independent Review" (December 1999), which was authored at MCA Engineers, Newport Beach, CA.

4. RECOMMENDATIONS

The three-year span of this Program was not long enough for many necessary S&T studies. For example, several hydroelastic models were advanced, and a validation experiment was completed, but after their development there was no remaining time left to either analyze the data or use it to validate the new models. As a second example, since those same hydroelastic models were not available until the end of the Program, the four preliminary system designs used existing, less-efficient models. Many other examples apply. This final Section describes unfinished tasks that are essential for a robust and reliable MOB design capability.

- ***User involvement.*** MOB development has been based on the 1995 MNS, which was never JROC-approved. That document included a wide range of missions but was primarily prescriptive in nature. The shifting nature of world politics and military development makes it difficult to develop a precise performance document. "Customer" involvement in the development process can only improve the quality of cost estimates and improve the focus of technical development. The joint MOB (JMOB) studies underway at the Institute for Defense Analysis, with report due to Congress by March 2001 may provide some insight here.
- ***Global response evaluation.*** Studies in this technology started with improvement of the state-of-the-art in hydrodynamic and hydroelastic analyses, and finished with completion of a series of hydroelastic laboratory-scale validation tests. However, there was not sufficient time to analyze the data or to use it to validate the new models. These global response models cannot be reliably used until they have been validated using this new test data. Completion of this effort is necessary to verify predictions of the wave field under a module, particularly for lighterage cargo transfer operations and air gap concerns in extreme seas. Validation of these global models is also necessary prior to the full MOB platform designs to minimize uncertainty about the connector loads and global responses while in the connected configuration.
- ***Cargo Transfer.*** The movement of cargo from MOB to shore is considered the logistic requirement with the most uncertainty. Additional S&T work is required to quantify the required cargo transfer rates, to identify and improve the ability of cargo handling equipment to transfer cargo from MOB, to quantify the capability of those transport craft for typical MOB stand-off distances, and to develop concepts for rapid transfer of material from MOB to shore.
- ***Classification Guide.*** The present preliminary version of the comprehensive Guide could not be completed within the time frame of this Program. Further development is necessary to quantify many of the parameters, such as the partial safety factors, and to incorporate the results from other uncompleted tasks such as wave coherence (see below).
- ***Dynamic Positioning.*** The cruise industry is advancing the development of azimuthing thrusters, and the offshore industry has continued improvements in the control of multiple thrusters for maintaining station with respect to a fixed reference. The MOB S&T Program used both of these advancements and further pioneered technology for multiple module stationkeeping and for the connection maneuvers among the modules. This effort needs to continue, with an emphasis on failure tolerance and reliability. This is important for three reasons. First, it is critical to maintain a straight runway for CTOL landings, (2) all multi-module connected platforms rely on dynamic positioning to keep the overall connector loads manageable, and (3) a reliable, multiple-module dynamic positioning system could conceivably be used instead of physical module connectors.
- ***Connectors.*** At the beginning of the program, concerns were raised about the ability of connectors to withstand the loads predicted by experiments conducted under a previous DARPA program. Connector loads are expected to be much larger than present industry practice and are

therefore still considered a major design issue, so much so that a significant portion of this Program's resources were directed towards this uncertainty (e.g., dynamic positioning, and the global response models and experiments). Platform designs have evolved toward extremely flexible connectors that trade increased relative motions for greatly reduced loads. As loads become smaller, connectors become easier to design and more reliable. Trading off decreased connector loads for increased runway motions must ultimately be validated through the "Global Response" effort discussed above.

- ***Metocean Environmental Specification.*** The accuracy of motion and load simulations for the longest connected platforms depends equally on the accuracy of: (1) the global response models and (2) the wind/wave/current excitation at that unprecedented scale. As described above, this S&T program produced a preliminary engineering specification for the environment at such scales, but some critical work remains, particularly for large-scale wave coherence. Completion of these pioneering studies (spanning from extreme/hurricane to swell wave conditions), along with validation of the global response models (listed above), are absolutely necessary in order to get accurate force maximum and fatigue estimates for elastic connector design.
- ***Exercise Classification Guide with more credible mission requirements.*** In addition to the Guide completion recommended above, it is strongly recommended to directly evaluate the final Guide with a representative platform design, perhaps based on mission recommendations expected from the ongoing IDA JMOB study. The present Guide was developed in parallel with the four system studies described above, so it is still largely untested. This critical evaluation of the final Guide would jointly verify the whole MOB design package consisting primarily of the Guide, the new hydroelastic tools, and the statistical/ probabilistic metocean environmental specification. Emphasis would be on consistency, possible computational excessive burden due to the probabilistic basis used in the Guide, and possible overlaps/gaps among the applicable military and commercial standards for analyses such as: survival to natural and hostile events, fatigue, operating dynamics, damage stability, inspections, etc.
- ***Validate the MOB design process at larger scale.*** The Program conclusion of MOB feasibility is based on analysis, laboratory and small scale testing, and the experience of the offshore industry. If the U.S. decides that MOB provides a credible and needed capability, the technology should be verified and validated at larger scale as part of a normal risk reduction program.

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Mission Requirements and Performance Measures

Appendix A

Mission Requirements and Performance Measures

1 OVERVIEW

1.1 General Description

This product area was divided into two categories: Mission Requirements Definition and Performance Measures Development. The objective of the first category was to define a set of baseline functional requirements for a range of MOB missions, based on the establishment of a rational and repeatable procedure for deriving specific requirements from a broadly worded statement of mission needs. The objective of the second category was to develop a rational procedure and the associated tools to evaluate the feasibility of MOB concepts on the basis of functional performance, operational availability, life cycle cost, and construction feasibility. Together, these data and tools provide a consistent basis for the development, refinement, and evaluation of different MOB concepts. This product area directly addressed the program objective of establishing feasibility and cost, by providing the assessment tools and a baseline set of mission requirements against which to evaluate the functionality, constructability, and life cycle cost of different concepts.

At the beginning of the MOB Program, the need for the Mission Requirements and Performance Measures product area had not been identified. However, initial negotiations with contractors for the development of conceptual point designs revealed that vastly different functional design bases had been used by each; the result of independent interpretations of the broadly worded Mission Needs Statement for the MOB. This led to the realization that a standardized process for developing the functional requirements was needed along with a suite of tools to evaluate the performance of these differing concepts.

The evaluation tools developed in this product area can be used to conduct sensitivity analyses and cost/benefit trade-off studies for unique sets of functional requirements. These will help identify the impact that evolving mission requirements will have on system performance, construction feasibility, and cost. The comparison of functional requirements to technology capabilities can also be used to validate the direction of the MOB science and technology efforts, or to redirect them to solve those technology issues most pertinent to developing the capabilities for design, construction and successful operation of a MOB.

1.2 Quality Assurance

Quality assurance measures for this product area included the establishment of a working group focussed on Mission Requirements and Performance Measures, participation in the semi-annual MOB Technology Exchange Conferences, an open deliverable review process for many tasks, and special coordination meetings between related tasks. Each of these quality assurance measures is described briefly below.

1.3 Mission Requirements and Performance Measures Working Group

A Working Group was established for this product area to coordinate the various requirements definition and documentation tasks, and to guide the development of the performance measure tools. The other functions of this working group were to ensure that the collective efforts spanned the widest range of candidate mission and platform concepts, and to serve as a forum for evaluation, comment, and the sharing of information and experience for the development of similar products. For example, three different tasks in this product area included the development of simulation models. Although the models simulate very different operations and had different purposes, those members of the Working Group developing models consulted each other regarding simulation software selection and model logic structure, bringing a wider range of experience and viewpoint to each of these efforts.

Working group meetings included technical status reports on all tasks, with comments and open discussion encouraged expanding the range of technical expertise involved in review. Guest attendance at the meetings also was encouraged, particularly for personnel from other Department of Defense (DoD) programs involved in requirements definition. Meetings held in conjunction with the semi-annual Technology Exchange Conferences were generally open to any MOB project team member interested. The working group members are shown in the table below. The working group met quarterly from October 1997 through March 1999.

Name	Organization
Michele Murdoch	Product Leader, Naval Facilities Engineering Service Center
Warren Baker	Naval Air Warfare Center
Bill Bender	University of Maryland
Roger Bostleman	National Institute of Standards & Technology
Don Bouchoux	Whitney, Bradley and Brown, Inc.
Ron Brackett	Naval Facilities Engineering Service Center
Dr. Dick Currie	McDermott Technologies, Inc.
Dr. Alok Jha	Bechtel National, Inc.
Dr. John Polky	Boeing, Inc.
Grant Sparks	Marine Corps Warfighting Laboratory
Jack Turner	Syntek, Inc.
Jim Wells	Boeing, Inc.
Dan Wilkins	Band, Lavis & Assoc.
Zach Zacharczenko	Naval Air Systems Command

The Working Group also served as an internal product area steering committee. By continually reviewing ongoing product developments and comparing this with problems or lack of data identified in other portions of the program, Group members were able to make recommendations regarding changes in priority, overall product area direction and addition of new studies. This self-review was responsible for the initiation of three research studies that had not been included in the original program plan. These additional studies included the development of a Concept of Operations for MOB as a platform to support Tactical Aviation and Carrier Battle Groups, Analysis of MOB Transit Speed Requirements, and C-17 payload and flight range capabilities and limitations.

1.4 Semi-Annual Technology Exchange Conference

All contributors to this product area were required to participate in the semi-annual MOB Technology Exchange Conferences and present a technical status report to the entire project community, with time allotted for comments and discussion. This often brought fresh viewpoints from MOB community members working in other product areas.

1.5 Deliverable Review Process

All deliverables were reviewed by at least two members of the MOB project office. The working group meeting technical status presentations also served as a preliminary review for works in progress, and team members often distributed draft documents to the entire working group for review. Several products, such as the requirements database and some early requirements documents were also made available to the entire MOB project community to elicit comments and recommendations. Where appropriate, NFESC and other Navy technical specialists in operational availability and modeling and simulation were asked to participate in the deliverable review process.

1.6 Special Review and Coordination Meetings

For certain groups of tasks, special coordination meetings were held to discuss details of technical direction, to ensure compatibility of products, and to promote the exchange of data between different tasks, and even across product areas. These included meetings between the requirements development tasks and the classification guide developers, between model developers and concept designers, and between different model development teams whose models would need to share data.

2 TECHNICAL ADVANCES

2.1 Key Issues

2.1.1 Mission Requirements

To effectively evaluate the functional and fiscal feasibility of a MOB, meaningful and consistent functional requirements had to be established. These requirements would establish the design basis for alternative MOB concepts, serve as measures against which to evaluate functional feasibility of different concepts, and help verify that the overall MOB S&T program was working on those technology issues most important to meeting the MOB mission requirements.

2.1.1.1 Requirements Derivation Process

In concert with establishing functional requirements for the MOB, it was desirable to establish a procedure and format for the derivation of functional requirements that would provide traceability for the derived requirements and flexibility to accommodate changes to the functional requirements as the MOB missions evolve. While general system engineering processes exist for deriving design requirements from broad mission needs, no detailed, repeatable and documented process existed for deriving the specific physical requirements. Such a process and method of documentation was needed to establish a traceable baseline set of requirements for the MOB and to provide a rational procedure for modifying the baseline functional requirements in the event that the final Mission Needs Statement (MNS) changes. It was of utmost importance that a consistent methodology for deriving the functional requirements be defined so that the process could be replicated as the underlying premises of missions (such as force size, support requirements, etc.) evolve.

2.1.1.2 Requirements Derivation

Prior to the ONR S&T program, no consistent set of functional requirements for a MOB had been defined. The only previously existing document defining MOB requirements was the draft MNS prepared in September 1995. Because MNS are intended to serve as broad statements of general mission needs, they are open to wide differences in interpretation in the development of engineering design criteria. This is reflected in the fact that each of the MOB concepts developed to date has been based on a different set of assumed requirements. Although each developer used this MNS as the basis for establishing the engineering design requirements, the different assumptions used in those derivations resulted in different design criteria for each concept. Because of this, an objective comparison of the different concepts has not been possible. In addition to needing a general evaluation of mission requirements to evaluate overall feasibility, some key operational requirements warranted a more in-depth analysis. These were identified as air operations, expected to dictate MOB length and width requirements, cargo handling operations, defining seakeeping and cargo handling requirements, and transit operations, defining propulsion requirements.

It must be noted that the ONR S&T program derived mission-based requirements for a MOB solely for the purposes of assessing technical feasibility and assuring that the Science and Technology (S&T) program addressed technical issues that were the most critical in meeting mission needs. When and if the MOB is considered for acquisition, specific mission-based requirements would be formulated as part of the formal U.S. DoD acquisition process.

2.1.2 Performance Measures

While the definition of mission-based requirements provided the baseline against which to evaluate different concepts, no consistent procedures or analytical tools existed for objectively assessing alternative MOB concepts. The mission requirements for MOB are expected to continue evolving, therefore it was important that any performance measurement tools be capable of quantifying the impact of changes in mission requirements on technical, functional, and financial feasibility. The specific key issues identified in the S&T program related to Performance Measures are described below. An important requirement for all performance evaluation tools to be used for MOB was that they provide flexibility to accommodate inevitable evolutions in the MOB mission, concept configurations, and support resources.

2.1.2.1 Completeness of Design

A systematic and repeatable method for evaluating the completeness of MOB designs with respect to necessary subsystems and space requirements was needed for assessing the different concepts. The results of these evaluations would indicate whether or not a given design had adequately accounted for mission space requirements and vessel subsystems volumes and weights. While existing design synthesis models could have been used to establish baseline designs and evaluate concept designs for more traditional monohull vessels, they are not applicable to semisubmersibles or to other unique aspects of the MOB structure and its operational requirements.

2.1.2.2 Evaluation of Overall Functional Performance

While other efforts in the S&T program focussed on evaluating the structural feasibility of a MOB, a method for evaluating the functional performance was identified as a critical need. This product area of the program thus focused on determining if a MOB could meet its operational requirements under the expected environmental conditions. A key requirement identified for this evaluation method was the capability to quantify the impact of changing mission requirements on technical and functional feasibility, enabling impact and sensitivity studies to be conducted as mission requirements evolved.

2.1.2.3 Evaluation of Functional Performance for Key Operational Requirements

While a general evaluation of functional mission requirements performance was needed to adequately evaluate feasibility, certain key operations were expected to drive the design requirements. In particular, the ability to conduct cargo transfer operations at sea was identified as a key operational ability warranting separate evaluation.

2.1.2.4 Life Cycle Cost

One of the primary objectives of the MOB S&T program was to establish a cost baseline for a MOB capable of meeting its mission requirements. No method for estimating the life cycle cost of a structure like the MOB existed at the beginning of the S&T program. While life cycle cost models exist for traditional vessels, they are not applicable to the unique structural and operational features of the MOB. Life cycle cost models do exist within the offshore industry for semisubmersible structures, but these are not available in the public domain, and they also do not address the MOB's unique features. A key requirement for life cycle costing for the MOB was that the method be capable of quantifying the cost impact from changes in mission requirements as the mission definition for the MOB evolves.

2.1.2.5 Construction Feasibility

Most of the MOB concepts developed to date comprise multiple semisubmersible modules that are several times larger than any semisubmersibles that currently exist. Construction feasibility for MOB was identified as a key issue that had to be addressed to adequately determine overall feasibility for a MOB. In particular, the capability of the U.S. offshore construction and shipyard industry to construct multiple MOB modules of unprecedented size needed to be evaluated, along with the identification of the risks and costs associated with different construction strategies.

2.2 Major Products

The tables that follow summarize the accomplishments achieved in this program towards requirements

definition and the development of tools to evaluate different MOB concepts. The sections that follow provide details on each of these specific tasks.

2.2.1 Mission Requirements (WBS 1.1)

WBS	Task	Advancement Achieved
1.1.1	Requirements Definition Process	A specific, repeatable and traceable process for deriving specific functional requirements from a broadly worded statement of mission needs was defined.
1.1.2	Functional Requirements Definition	Functional requirements supporting a range of MOB missions were derived from the MNS, with the process documented in Concepts of Operation, System Capabilities Documents, and Performance Requirements Documents for four separate MOB missions.
1.1.3	Database Development	A hierarchical database documenting the baseline set of functional requirements and the derivation process was developed and populated.
1.1.4.1	Air Field Requirements Study	Airfield requirements for length and width were established for C-17 operations. Preliminary evaluation of runway discontinuity limits was completed.
1.1.4.2	Air Operations Conditions Study	A credible worst case for air operations on the MOB was established, in terms of environmental and aircraft conditions.
1.1.4.3	Air Operations Safety Analysis	Collision and obstacle avoidance requirements for MOB airfields were defined. Initial air operations safety analysis of one candidate configuration was completed.
1.1.5	Cargo Handling Requirements and State-of-Practice assessment	Functional requirements for crane related cargo handling for Lift-On, Lift-Off (LO/LO) operations were defined for MOB. An assessment of the current state-of-practice and ongoing research related to crane automation and motion compensation was completed.
1.1.6	Transit Speed Study	Minimum transit speed requirements for both inter- and intra-theatre transit operations were established for MOB.

2.2.2 Performance Measures (WBS 1.2)

WBS	Task	Advancement Achieved
1.2.1	Life Cycle Cost Structure Definition	A general life cycle cost structure for the MOB was derived from a standard ship life cycle cost structure.
1.2.2	Design Synthesis Model and Enhanced Life Cycle Cost Model	An existing design synthesis model for traditional vessels was enhanced to accommodate MOB-like structures. A life cycle cost model embedded in the model also was modified to better reflect the unique structural and operational features of a MOB. A preliminary evaluation of some early concept designs was completed using the models.
1.2.3	Operational Availability Model	An operational availability model was developed capable of evaluating a wide range of MOB concepts on the basis of mechanical and structural reliability, environmental conditions, and operational mission fulfillment for complex missions. The model includes an embedded database of 23 years of wave, wind and current data for 22 sites worldwide.
1.2.4	Ship Cargo Transfer Rate Model	A suite of three models was developed, which simulate the transfer of Lift-On/Lift-Off and Roll-On/Roll-Off between a MOB and a vessel alongside, taking onto account cargo handling system parameters and the relative motions between the vessel and the MOB. A preliminary analysis of cargo transfer rates for one MOB concept and three vessel classes was completed.
1.2.5	Construction Feasibility Assessment – Method, Analysis, and Constructability Guidelines	A risk-based method for evaluating MOB construction strategies and simulation models for the construction of five different MOB concepts using two different construction strategies were developed. An evaluation of constructability for these five concepts also was completed. Preliminary construction guidelines for MOB were defined.

3 PRODUCTS DESCRIPTION

3.1 Mission Requirements (WBS 1.1)

3.1.1 Requirements Definition Process (WBS 1.1.1)

Syntek Technologies was tasked to develop and document a rational, repeatable and traceable process for deriving specific functional requirements from a broad-based Mission Needs Statement. It was of utmost importance that this effort develop a consistent methodology for deriving the functional requirements so that the process can be replicated as the underlying premises of missions (such as force size, support requirements, etc.) evolve.

3.1.1.1 Advancements

Syntek Technologies developed a documented, repeatable and traceable process for deriving specific requirements from a broadly based statement of mission needs within the S&T program. While this process was developed for deriving baseline requirements for a MOB, the process itself is generic and can be applied to virtually any other system. A system engineering based process was selected for deriving the specific mission-based functional requirements for the MOB. This process begins with the 1995 draft MNS for the MOB, and methodically deconstructs the broad-based MNS into multiple discrete missions for which a Concept of Operation (CONOPS) is developed. For systems with less complex missions, this step of the process could be omitted, with a single CONOPS satisfying all mission elements.

The CONOPS developed for each mission describes the operational environment and the specific roles that the MOB plays in supporting the planning, deployment, reception and operations phases of a mission. Each CONOPS serves to establish the basis for a System Capabilities Document (SCD). This document identifies the specific capabilities the system will need to provide to support the CONOPS. Each specific capability identified in the SCD is further decomposed into specific functional requirements needed to provide that capability. These requirements are documented in a Performance Requirements Document, or PRD. The final product of this process is a set of Design Evaluation Criteria, rolling up all physical requirements from the PRDs into an all-encompassing set of mission-based requirements identified for the MOB, expressed in engineering units. The Design Evaluation Criteria is to encompass all requirements needed to perform any of the discrete missions defined for MOB.

Figure A-1 illustrates the requirements derivation process and the correlation of process steps with the requirements documents described above. The actual development of these documents for MOB is described below in Appendix A, Section 3.1.2 (WBS 1.1.2).

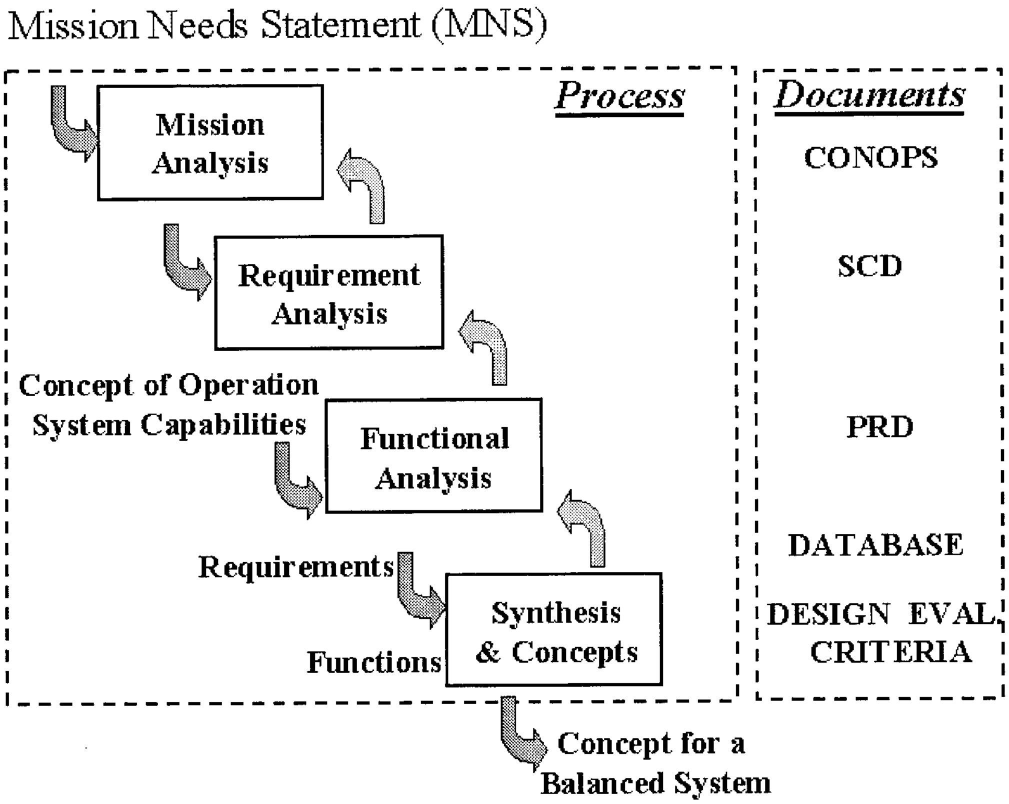

Figure A-1. System Engineering Process for Derivation of Requirements.

3.1.1.2 Products

1. Naval Facilities Engineering Service Center, Overview of Preliminary Requirements Documents and Requirements Derivation Process, June 1998.

3.1.1.3 Resource

Syntek Technologies, Inc.

3.1.2 Requirements Derivation (WBS 1.1.2)

Syntek Technologies Inc., Band, Lavis and Associates, and Whitney, Bradley and Brown Inc. were tasked with the development of the principal requirements documents and derivation of baseline requirements using the process developed in WBS 1.1 (see Appendix A, Section 3.1.1). The results of this work are needed to establish meaningful baseline requirements for evaluating the feasibility of the MOB. This task included the identification of multiple discrete missions that would encompass the entire draft MNS, and for each mission developing the Concept of Operations, Systems Capability Document, and Performance Requirements Document. Tasking to Syntek also included the compilation of the Design Evaluation Criteria, encompassing all requirements from the multiple PRDs into a single set of physical criteria that would describe a MOB capable of meeting all identified missions.

The tasking to develop the Design Evaluation Criteria also included a reconfigurability assessment of the MOB. Reconfigurability is an important factor in the efficient use of the space on board the MOB, if as expected, the MOB is to be utilized during several phases of an operation and by multiple organizational units. These different phases and occupancies of the MOB over the course of a given operation will by necessity overlap in space utilization and time. The purpose of this task was to better define the requirements for reconfigurable space on board the MOB, and possibly lead future designers to more efficiently allocate and outfit spaces onboard MOB modules.

3.1.2.1 Advancements

Because there was no one single mission that would plausibly cover all of the requirements contained in the 1995 MNS, Syntek Technologies identified the following four separate missions that together cover all of the mission elements contained in that document:

1) ***Logistics Hub.*** In this mission, the MOB serves as a forward base in a logistics network for prepositioning, receiving, warehousing, and distributing equipment and supplies to sea, air, and land forces.

2) ***Operational Maneuver From the Sea (OMFTS):*** In this mission the MOB serves as a seabase providing combat service support for up to 20,000 Marines. The seabase provides a platform for the "marrying-up" of Marine Air Ground Task Force (MAGTF) personnel with Marine Preposition Force (MPF) equipment. It serving as the command and control center for the seabased operation and provides indefinite sustainment to the troops once ashore. Other combat service support functions such as maintenance and health service are also supported from the seabase.

3) ***Special Operating Forces:*** In this mission the MOB provides support for Joint Special Operations Task Forces, including staging, logistical support, maintenance, and regeneration of combat units.

4) ***Tactical Aviation Support Operations:*** In this mission the MOB provides support for air operations initiated by other military assets, including search and rescue, alternative landing, aircraft maintenance, stopover point, intelligence, and surveillance.

In following the requirements derivation process, Syntek developed a CONOPS, SCD and PRD for each of these discrete missions. A notional force list and plausible scenario describing a hypothetical operation in a specific geographic location to illustrate how a MOB might support an actual mission were identified

for each CONOPS. The CONOPS development for the Tactical Aviation (TACAIR) Support mission was an especially important study because of the runway length requirements needed to support various tactical aircraft, with runway length being perhaps the most significant driver of MOB feasibility and cost. The most important result of that effort was clear identification of landing and take-off distance requirements for a wide variety of aircraft. This summary clearly shows the capabilities associated with different MOB runway lengths. The TACAIR Support CONOPS development effort complemented the Airfield Dimensions and Roughness study described in Appendix A, Section 3.1.4.1 (WBS 1.1.4.1).

In addition to serving as the basis for evaluating the suitability of different MOB concepts, and for the advancement and refinement of future designs, the requirements developed in this task impacted several areas of the program. Some of the requirements had direct impacts on the standards and criteria being developed as part of the MOB *Classification Guide*. For example, the survivability requirements identified for the MOB require suitable structural design criteria to ensure that the MOB can survive against the projected threats. One of the most important benefits of the requirements derivation work to the S&T program was the ability to compare mission-based requirements to existing technology capabilities. This comparison verified that the S&T efforts were focused on solving those technology problems most critical to meeting the MOB's mission requirements.

A draft Design Evaluation Criteria was developed, encompassing all of the requirements identified in the four PRDs, but due to limited resources a final version of the document was not prepared. The draft is considerable unsuitable for release. Again due to limited resources, Syntek was not able to complete the reconfigurability analysis included in the original tasking.

3.1.2.2 Products

2. Lopez, P.M., Mission Requirements for the Mobile Offshore Base, Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99, Honolulu, HI, September 22-24, 1999, Volume I, pp.433-442.

3. Syntek Technologies, Inc., Concept of Operations for Operational Maneuver From The Sea (OMFTS), Version 1.3, March 1999.

4. Syntek Technologies, Inc., Concept of Operations for Special Operations Forces (SOF), Version 1.3, March 1999.

5. Syntek Technologies, Inc., Operational Scenario – Logistic Concept for MOB, July 1999.

6. Syntek Technologies, Inc., Operational Scenario – Operational Maneuver From The Sea (OMFTS) Concept for MOB, July 1999.

7. Syntek Technologies, Inc., Operational Scenario – Special Operations Forces (SOF) Concept for MOB, Version 1.1, July 1999.

8. Syntek Technologies, Inc., Operational Scenario – Tactical Aircraft Support (TACAIRSUP) Concept for MOB, Version 1.0, July 1999.

9. Syntek Technologies, Inc., Performance Requirement Document (PRD) – Logistics Concept for MOB, Version 2.0, February 2000.

10. Syntek Technologies, Inc., Performance Requirements Document (PRD) – Operational Maneuver From The Sea (OMFTS) Concept for MOB, Version 2.0, February 2000.

11. Syntek Technologies, Inc., Performance Requirements Document (PRD) – Special Operations Forces (SOF) Concept for MOB, Version 2.0, February 2000.
12. Syntek Technologies, Inc., Performance Requirements Document (PRD) – Tactical Air Support (TACAIRSUP) Concept for MOB, Version 2.0, February 2000.
13. Syntek Technologies, Inc., System Capabilities Document (SCD) for Logistics, Version 1.4, February 2000.
14. Syntek Technologies, Inc., System Capabilities Document (SCD) for Operational Maneuver From The Sea (OMFTS), Version 1.4, February 2000.
15. Syntek Technologies, Inc., System Capabilities Document (SCD) for Special Operations Forces (SOF), Version 1.4, February 2000.
16. Syntek Technologies, Inc., System Capabilities Document (SCD) for Tactical Aircraft Support (TACAIRSUP), Version 1.3, February 2000.
17. Syntek Technologies,Inc., Concept of Operations for Logistics, Version 1.3, March 1999.
18. Whitney Bradley and Brown, Inc., TACAIR CONOPS for TACAIRSUP, July 1999.

3.1.2.3 Resources

Syntek Technologies, Inc., was tasked with the identification of discrete missions from the MNS, development of the Logistics, OMFTS and Special Forces CONOPS, all four SCDs and PRDs, the development of the Design Evaluation Criteria, and the reconfigurability assessment.

Whitney, Bradley and Brown, Inc., developed the CONOPS for the Tactical Aviation Support mission.

Band, Lavis and Associates derived functional requirements for the MOB, tied back to the MNS and other source documents.

3.1.3 Requirements Database Development (WBS 1.1.3)

As a means of documenting both the requirements derivation process and the baseline set of functional requirements derived for the S&T program, Band, Lavis and Associates, Inc. was tasked with the development and population of hierarchical database. The purpose of the database was to serve as a traceable and annotated repository for the baseline set of functional requirements derived under the requirements derivation task (Appendix A, Section 3.1.2, WBS 1.1.2), and to document the requirements derivation process itself.

3.1.3.1 Advancements

Band, Lavis and Associates, Inc. and populated a hierarchical database to serve as a repository for both the baseline functional requirements and as a means of documenting the derivation process itself. The first three levels of decomposition of the MNS (mission elements from the CONOPS, capabilities requirements in the SCD and the functional requirements reflected in the PRD) are documented in the database. Each entry is annotated with references to source documents such as the MNS, approved doctrine, or accepted design guidance. The database can be updated as MOB applications and technologies evolve, with the annotation feature providing a means to document the evolution.

The database is structured with mission elements at the top level, with each element linked to the platform capabilities needed to meet that mission element. Each capability is in turn linked to all of the specific functional and physical requirements needed on the MOB to meet that capability. Because the top level of the database consists of individual *mission elements* instead of the four CONOPS representing an overall mission, it allows the user to build new missions from the list of elements and not be tied to the four missions selected for initial CONOPS development. This helps ensure that the database and the requirements documented in it will remain useful tools for the MOB program as missions and CONOPS for the MOB evolve with time. Figure A-2 illustrates the hierarchical nature of the database, and its ties to the requirements derivation process and requirements documents produced during that process.

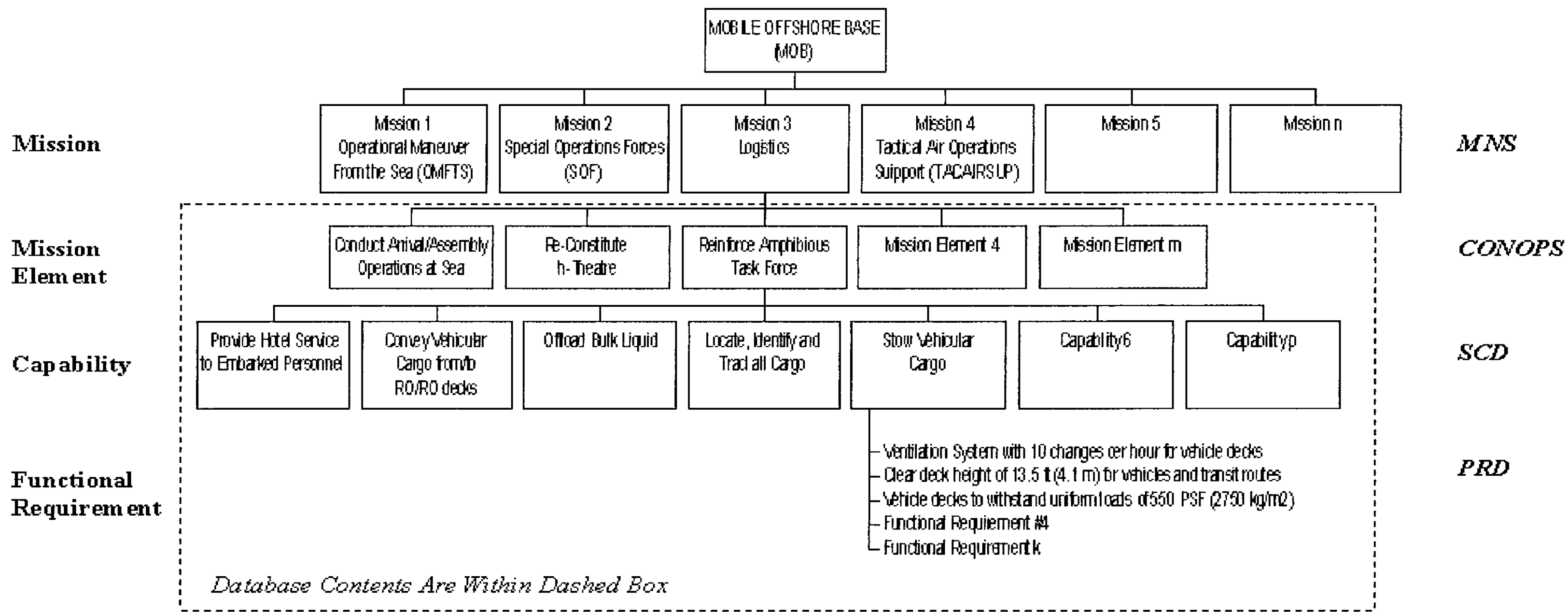

Figure A-2. Example of Requirements Derivation Process Documented in Database Structure.

In addition to documenting the functional requirements identified for the MOB S&T program, the database can be used to conduct sensitivity studies for evaluating the impact that changes in missions have on functional requirements for the MOB. This feature will help identify those specific elements of a particular mission responsible for driving MOB requirements, and any associated technology advancements needed to fulfill them.

The database will be available to future MOB planners and designers for use in developing engineering design requirements for the MOB. Output from the database also serves as input for the PASS design synthesis model that has been expanded to accommodate MOB-like structures (see Appendix A, Section 3.3.2, WBS 1.2.2). Because many of the mission elements included in the database are not unique to MOB operations, this database also is a valuable planning and sensitivity analysis tool for platforms other than MOB.

3.1.3.2 Products

1. Band, Lavis and Associates, Inc., Missions/Capabilities/Functional Requirements Database – Final, 15 December 1998.

3.1.3.3 Resource

Band, Lavis and Associates Inc.

3.1.4 Air Operations Requirements (WBS 1.1.4)

While design and operating criteria for air operations on vessels at sea exist for many aircraft, current MOB missions also include operations with land-based aircraft such as the C-130 and C-17, for which sea-based criteria are not available. Accurate identification of airfield operations is critical to both operational and structural feasibility of a MOB since air operations are expected to dictate both the length and width requirements for the platform as well as the relative motion limitations between connected modules. Air operations requirements are also expected to have dramatic impacts on maintainability, operating cost and operational availability of the system. In addition to the derivation of general physical requirements for the MOB from the 1995 MNS, the following tasks were sponsored under this program to more finely evaluate the requirements associated with air operational requirements for the MOB.

3.1.4.1 Airfield Dimensions and Roughness (WBS 1.1.4.1)

The Naval Air Warfare Center Aircraft Division (NAVAIRWARCENACDIV) was tasked with defining general air operations requirements, including runway width, length, and surface discontinuity limitations, as well as operating environment limitations such as wind and platform motion limitations. The issue of limitations for runway discontinuities is especially critical to the feasibility of a MOB, as all of the prominent concepts considered to date include some measure of angular discontinuity at the connection point between platforms, with the magnitude of the discontinuity dependent upon relative motions of adjacent platforms.

3.1.4.1.1 Advancements

This initial investigation indicated that a 6,000 ft long and 450 ft wide MOB would be adequate to conduct aircraft operations for the wide variety of aircraft considered. The results also identified air operations systems to help minimize the length requirements for the MOB and maximize aircraft payloads (Figure A-3). Some of the most important results from this study were from the analysis of acceptable runway discontinuities that would be allowable for various aircraft as they transited across adjoining MOB modules. This part of the study was conducted with the assistance of the Army Corps of Engineers Airfield and Pavements Division of the Waterways Experiment Station, and applied their analytic model of landing gear dynamics to the unique problem of runway discontinuities created by the inter-module connections of the MOB.

3.1.4.1.2 Products

1. Naval Air Warfare Center, Aircraft Division, Mobile Offshore Base Aircraft Operations Criteria and Analyses, Report NAWCADLKE-MISC-481500-0037, March 1999.

3.1.4.1.3 Resources

Naval Air Warfare Center Aircraft Division.

Army Corps of Engineers Airfield and Pavements Division of the Waterways Experiment Station.

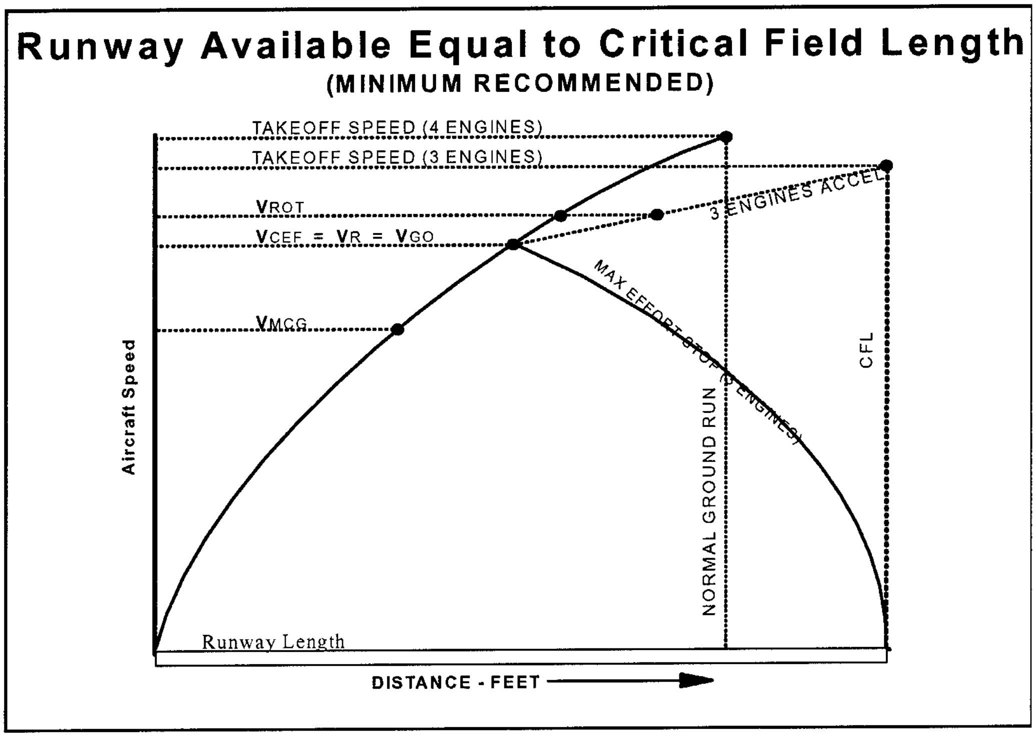

Figure A-3. Critical runway length.

3.1.4.2 Air Operations Conditions - Credible Worst Case (WBS 1.1.4.2)

As concept designs were developed and airfield requirements were defined within the S&T program, it was discovered that different assumptions for air operations on the MOB craft were being used. This lead to analysis results, which showed different capabilities for airfields with the same dimensions. For example, a runway length derived for dry conditions may not be adequate for the same aircraft when wet or with one or more engines out. If all of the possible worst case operating conditions were applied at the same time, the required length of the MOB runway would increase to an unrealistic value. A decision was made that part of the requirements definition effort should include the definition of a "credible worst case" for air operations, addressing both environmental considerations and aircraft operating parameters. The purpose of establishing a "credible worst case" was to define that combination of operating parameters that would constitute a reasonable worst case situation to base the airfield design upon. Selecting the "worst case" from all environmental parameters and operating conditions would not have been representative of reasonable operations, since all "worst case" conditions being present at the same time (e.g., simultaneous heavy rain, high temperature, no wind, full payload and engine failure) is highly improbable. This would lead to an overly conservative and wasteful design.

3.1.4.2.1 Advancements

Whitney, Bradley and Brown Inc., identified that combination of parameters comprising a "credible worst case" for both environmental and aircraft operating conditions, for both take-off and landing. The study

addressed operating conditions for high-performance, jet or turbo-prop aircraft that perform tactical missions for the U.S. Air Force, Navy and Marine Corps. Two "worst case" environmental situations were identified that define the operating envelope to be met by MOB design efforts, each addressing temperature, humidity and runway wetness. For aircraft operating conditions, "worst case" conditions were identified for both landing and take-off. The study also identified differences in U.S. Air Force and U.S. Navy operating procedures that could impact the length requirements for MOB runways.

3.1.4.2.2 Products

1. Bouchoux, D.R. and J.M. Lillard, Mobile Offshore Base (MOB) Tactical Air Operations Credible Worst Case, Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99, Honolulu, HI, September 22-24, 1999, Volume I, pp. 408-414.
2. Whitney, Bradley and Brown, Inc., Mobile Offshore Base (MOB) Tactical Air Operations Credible Worst Case, August 1999.

3.1.4.2.3 Resources

Whitney, Bradley and Brown, Inc.

3.1.4.3 Airfield Safety Requirements (WBS 1.1.4.3)

As part of their work on development of the Kvaerner Sea-Base concept for a MOB, the Boeing Company was tasked with establishing airport design requirements for a baseline MOB, developing a conceptual airfield layout plan, and analyzing the relative safety of the layout. The purpose of this effort towards requirements definition was to establish the collision and obstacle avoidance requirements for MOB airfields. It is notable that air operations were determined to be so critical to the feasibility assessment of a MOB, and because of the lack of defensible functional requirements related to air operations at that time, air operations study subcontracts were established with both Boeing and McDonnell-Douglas. The McDonnell-Douglas study is addressed under the Alternative Concepts product area (see Appendix D).

3.1.4.3.1 Advancements

The Boeing Company methodically developed a conceptual airfield layout for the MOB and analyzed it for safety using the International Civil Aviation Organization (ICAO) Collision Risk Model. The configuration was analyzed for missed Instrumented Landing System (ILS) approaches (Figure A-4), estimated runway overrun, and excursion rates. The most important aspect of this effort was the progress made in understanding the operational safety of air operations conducted from a MOB. The results also helped identify the most significant obstacles for aircraft collision on the conceptual layout and identified that aircraft landings (vice take-offs) pose the greatest risk to air operations safety on the MOB. The study also pointed out the increased likelihood and catastrophic nature of overrun events on the MOB compared to land-based operations. These results help to establish collision and obstacle avoidance requirements for MOB airfields. The point analysis also indicated that the total risk for the configuration evaluated was well below the ICAO Target Level of Safety, advancing the validation of feasibility for MOB air operations.

3.1.4.3.2 Products

1. Boeing Company, Mobile Offshore Base Feasibility Study Airfield Requirements Report, March 2000, Rev. A.
2. Polky, J.N., Airfield Operational Requirements for a Mobile Offshore Base, Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99, Honolulu, HI, September 22-24, 1999, Volume I, pp. 206-211.

3.1.4.3.3 Resource

The Boeing Company, as a subcontractor to Kvaerner Maritime.

Total risk for baseline case = 6.5E-08

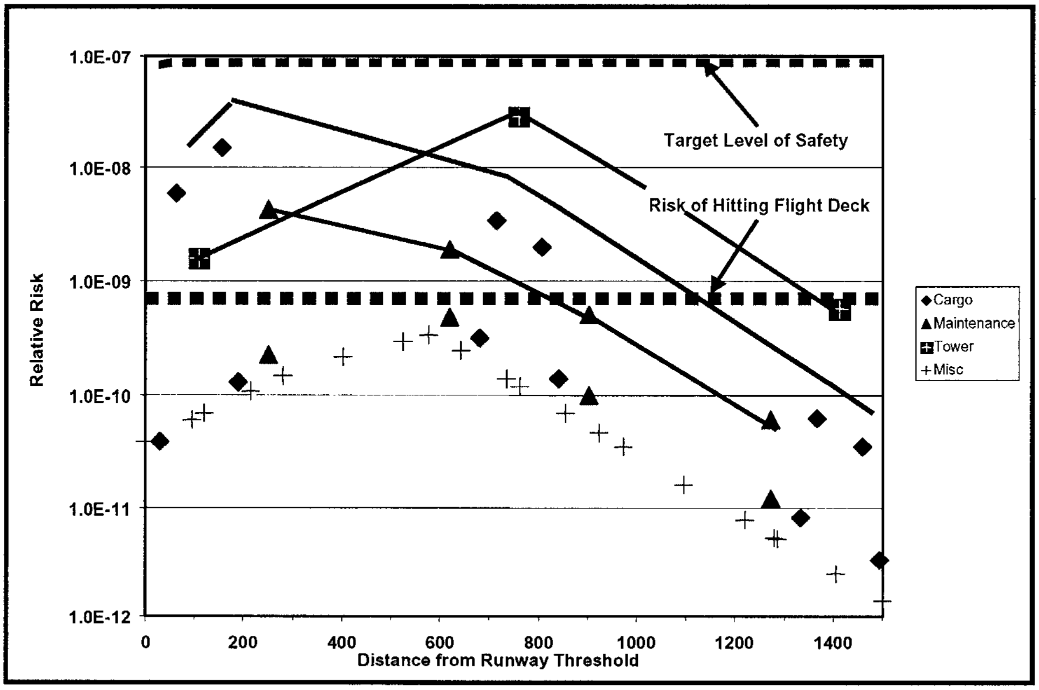

Figure A-4. Collision risk analysis results from airfield configuration study.

3.1.5 Containerized Cargo Handling Requirements and State-of-Practice Assessment (WBS 1.1.5)

The National Institute of Standards and Technology (NIST) was tasked with developing the physical requirements specific to meeting the containerized cargo transfer goals for the MOB, in terms of crane capabilities, clearances, and related ship interface issues. This was a high priority issue due to the vast amount of containerized cargo that would need to be transferred between a MOB and cargo ships during operations, and because of the difficult open-ocean environment in which the MOB would normally be required to operate. NIST also was tasked with assessing the current state of practice in crane automation and motion compensation relative to the needs of the MOB. The purpose of this effort was to establish a baseline of capabilities and identify critical technology areas and needs for further research to meet cargo handling requirements.

3.1.5.1 Advancements

Crane requirements for handling containerized cargo in terms of crane reach, accessibility to container cells onboard ship, hook height and clearance over container ships, airspace restrictions, operational sea states for cargo handling operations, and structural considerations were identified in this study. Throughput, cargo stowage and retrieval, crane stowage, and other design recommendations also were developed.

The current state-of-practice and ongoing research in all aspects of crane automation and motion compensation was assessed and documented. The resulting report identifies sixty-two different efforts focused on these critical technology areas. The report thoroughly describes the goal and status of each effort, and establishes a technology baseline for crane automation and motion compensation, making this reference volume valuable to the entire logistics community.

3.1.5.2 Products

1. National Institute of Standards and Technology, Cargo Container Transfer Requirements for the Mobile Offshore Base, April 1998.
2. National Institute of Standards and Technology, Survey of Cargo Handling Research Relative to the Mobile Offshore Base (MOB) Needs, 2 July 1998.

3.1.5.3 Resource

The National Institute of Standards and Technology.

3.1.6 Transit Speed Requirements (WBS 1.1.6)

Whitney, Bradley and Brown, Inc., was tasked with the development of baseline transit speed requirements for the MOB, for both inter- and intra-theatre transit. The results of this effort are especially important to defining technical feasibility for a MOB, as they establish the requirements for the propulsions systems and hull-form that will be required on each MOB module.

3.1.6.1 Advancements

Whitney, Bradley and Brown's transit speed study, which was based on the results of recent war games (Figure A-5), indicated that moderate trans-oceanic speeds of twelve knots are adequate to meet currently projected mission needs for both inter and intra-theatre transit for the MOB (Figure A-6). The defined speed requirement helps validate the feasibility of the MOB, as the propulsion system design efforts undertaken in the Alternative Concepts product area of the S&T program indicate that twelve knots is possible for the systems proposed to date, and is well within the capacity of current technology.

3.1.6.2 Products

1. Whitney, Bradley and Brown, Inc., MOB Transit Speed Requirements Analysis, 30 November 1998.

3.1.6.3 Resource

Whiney, Bradley and Brown, Inc.

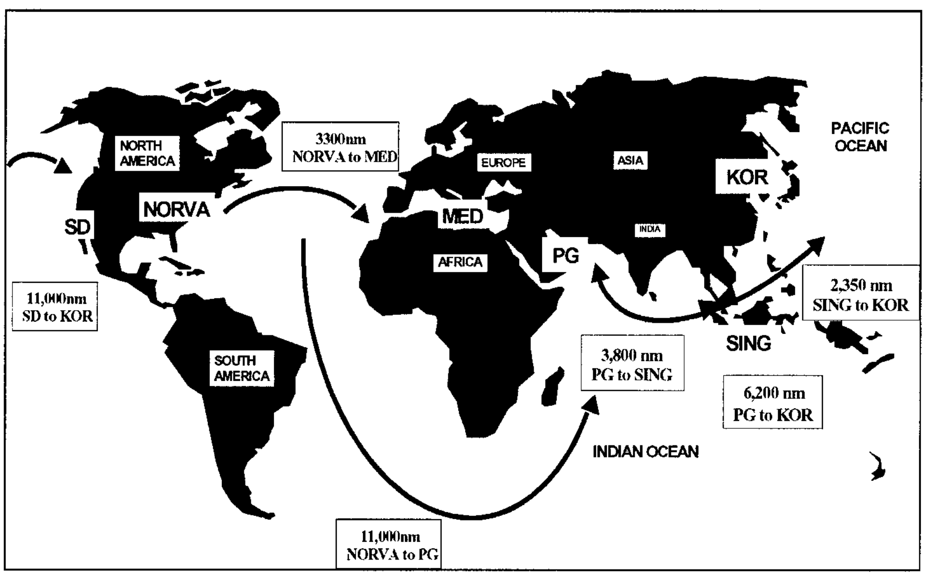

Figure A-5. Potential intra-theater transit routes.

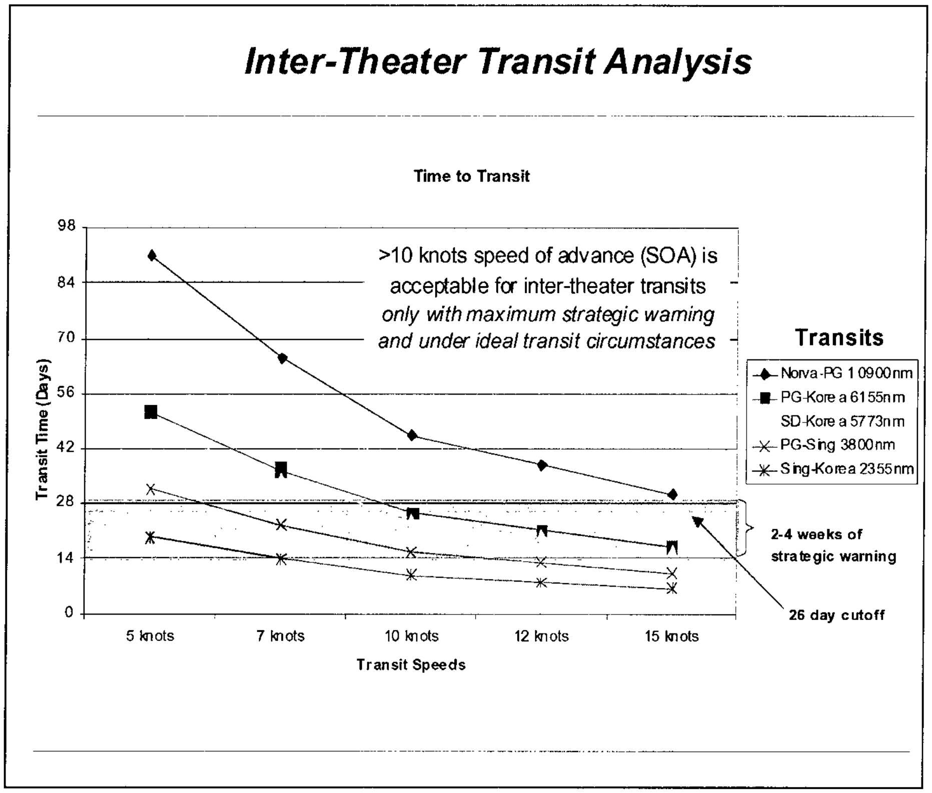

Figure A-6. Results of inter-theater transit speed analysis.

3.2 Performance Measures (WBS 1.2)

3.2.1 Life Cycle Cost Structure (WBS 1.2.1)

Syntek Technologies Inc. was tasked with the development of a basic life cycle cost structure for a MOB to be used in establishing a baseline cost estimate for a MOB capable of meeting its intended mission. It was also desirable to establish a comprehensive life cycle structure as a standard for comparison against designer-generated cost estimates that may have included fewer or different cost elements.

3.2.1.1 Advancements

A general life cycle cost structure for the MOB was derived from a standard ship life cycle cost structure (Figure A-7). The structure includes the major categories of design phase, production phase, operating and support phase, including demilitarization and disposal. Cost elements are identified hierarchically to the fourth level, and major cost elements were defined in detail. The elements of this life cycle cost structure were considered during the enhancement of the life cycle cost model, which were embedded in the design synthesis model (see Section 3.2.2, WBS 1.2.2 below).

3.2.1.2 Products

1. Syntek Technologies, Inc., Life Cycle Cost Elements Structure (LCCE), September 1998.

3.2.1.3 Resource

Syntek Technologies, Inc.

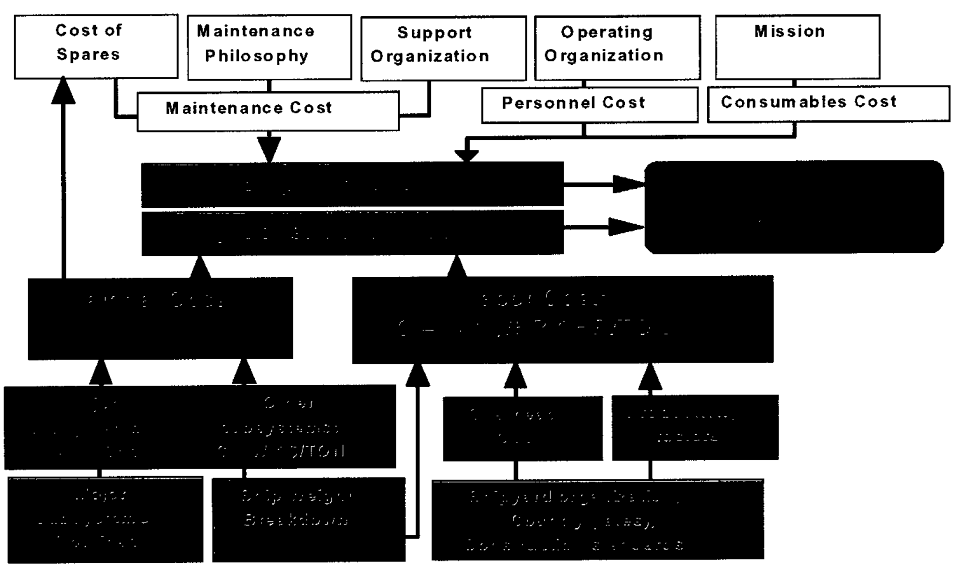

Figure A-7. Top level diagram of MOB life cycle cost model.

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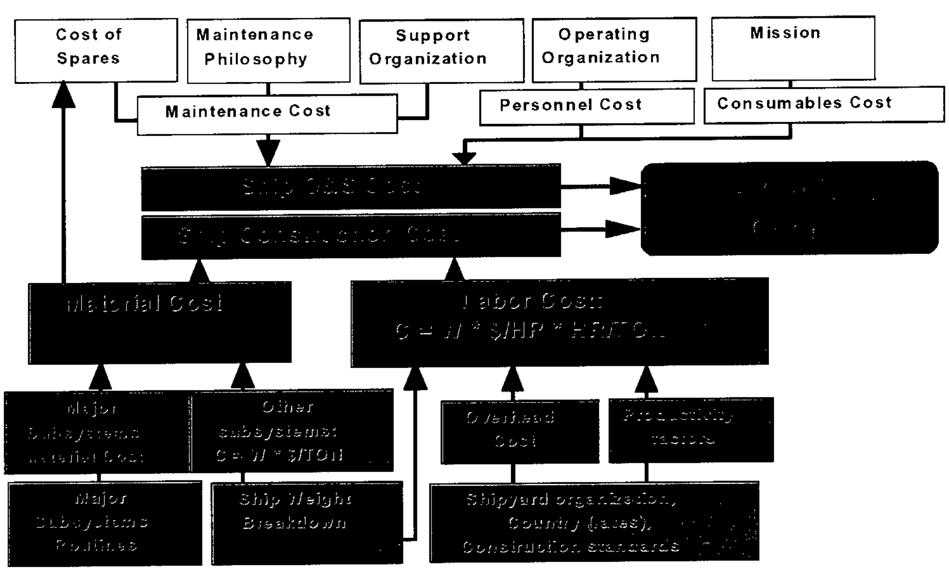

Figure A-7. Top level diagram of MOB life cycle cost model.

3.2.2 Design Synthesis Tool and Enhanced Life Cycle Cost Model (WBS 1.2.2)

Band, Lavis and Associates, Inc. was tasked with the expansion of an existing design synthesis model that could be used to both establish a baseline geometry for a MOB capable of meeting the functional requirements, and for evaluating the ability of candidate MOB designs to accommodate all necessary subsystems and space requirements. This performance evaluation tool serves the primary S&T goal of establishing feasibility by providing a means to evaluate the overall validity of different concept designs and life cycle cost estimates. The model also serves to evaluate the effects of changing mission requirements or subsystem technology on performance and system cost.

3.2.2.1 Advancements

Band, Lavis and Associates, Inc. enhanced the existing PASS model, previously developed for the Naval Sea Systems Command (NAVSEA), to accommodate MOB-like structures and their unique operations and life cycle cost factors. PASS is a whole-ship design synthesis model that uses an experience-based rule set to determine whether a given design provides reasonable geometry, weight, volume, and other parameters for specified systems and performance characteristics (Figure A-8). The original monohull model was expanded to accommodate internal arrangements for a MOB semisubmersible, including all major subsystems, and then exercised to evaluate the completeness of those alternative MOB concepts adequately advanced to allow evaluation at the close of FY98. The semisubmersible hull designs were accommodated by a modification to a catamaran design module included in PASS. The enhancements to PASS did not include a means for evaluating connections or other interfaces between MOB modules.

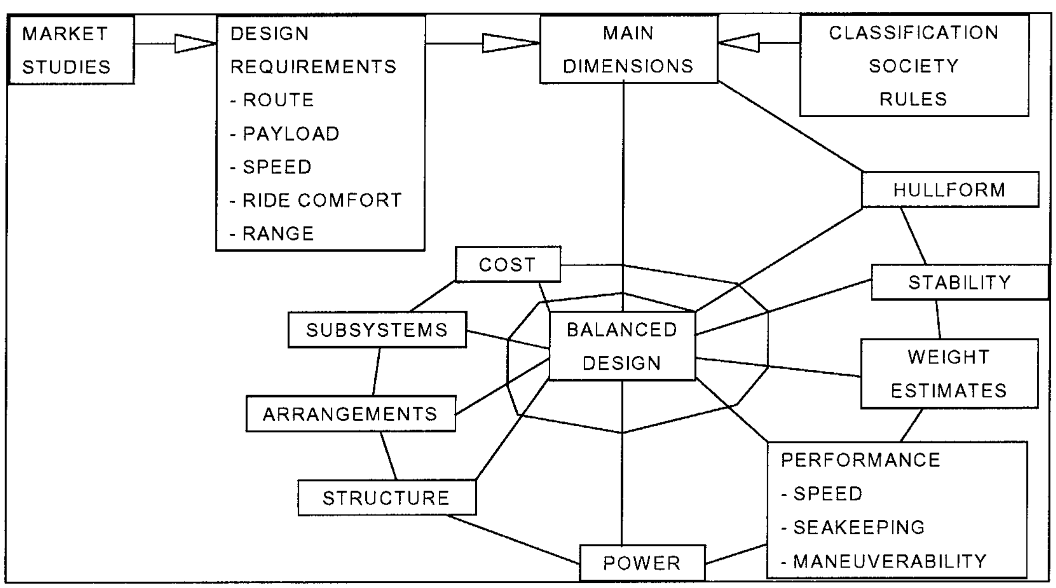

Figure A-8. Illustration of typical ship design spiral.

The model also was enhanced to accommodate designs using reinforced concrete for the hull. As part of this effort, an annotated bibliography of design guidance, recommended practices and experience with concrete in the marine environment was compiled.

Completeness of design was evaluated in terms of basic geometry and space and volume requirements, and required subsystems and subsystem capacities. This was done for each of the major missions identified for MOB. The evaluation confirmed that those designs were reasonable in terms of basic geometry, weights, and subsystems. The study also identified that all of the designs, with the possible exception of the Kvaerner concept, provided between two to three times the storage volume required to meet any one of the candidate missions. The extra volume is a result of the length and width of the MOB conceptual designs being driven by the requirement for CTOL air operations. Based on these findings, it is apparent that the MOB could simultaneously support more than one mission, or be much smaller if there were no requirement for fixed wing aircraft operations. These results also suggest that a MOB composed of non-identical modules (similar to the concept being developed by Kvaerner with one or two equipment storage and repair modules and the remainder being runway only modules) may offer potential for cost savings during fabrication and operation of a MOB.

The acquisition and life cycle cost model embedded in PASS was also enhanced to better represent MOB-specific structural features and operations, with the intended use of evaluating the relative cost of concepts developed within the S&T program and to validate the individual designer's own cost estimates. However, the cost model in PASS was not able to accommodate a vessel the size of the MOB, and cost estimates in this task had to be developed outside of PASS.

It must be noted that there remains some question regarding the applicability of the structural design facets of the PASS model to a vessel of the sheer size of MOB. The developer has recommended that an investigation be conducted to ensure that the enhancements to the model have not exceeded the limits of scalability.

Once verified for use on MOB-like structures, the expanded PASS will serve as a valuable tool to any ongoing or future MOB program in terms of evaluation, design refinements, and benchmarking. With the inclusion of a corrected cost model, PASS could be used to evaluate the impact of changing mission requirements, technology capabilities and operating environments on system performance and cost.

3.2.2.2 Products

1. Bagnell, D.G. and B.G. Forstell, The Use of Design Synthesis Tools for Conducting Trade and Cost Studies for Very Large Floating Structures, Proceedings of the 3rd International Workshop on Very Large Floating Structures (VLFS '99), Honolulu, HI, September 22-24, 1999, Volume I , pp. 198-205.

2. Band, Lavis and Associates, Inc., Concrete Technology for Offshore Structures - Bibliography, 15 April 1998.

3. Band, Lavis and Associates, Inc., Development and Utilization of PASS for Parametric Design Analysis of MOB Concepts, December 1999.

3.2.2.3 Resource

Band, Lavis and Associates, Inc.

3.2.3 Operational Availability Model (WBS 1.2.3)

Bechtel National, Inc. was tasked with the development of a simulation-based operational availability (Ao) model for quantitatively evaluating the functional performance of different MOB concepts at particular sites relative to mission-derived performance criteria. Specific goals identified for the model were:

1) Provide a means for evaluating the sensitivity of overall MOB operational availability to changes in reliability or availability of various subsystems,
2) Evaluate the sensitivity of various performance parameters to changes in concept configuration and mission requirements, and
3) Assess the effect of the environment at various possible deployment sites on the ability of the MOB to perform critical mission related operations.

This Ao model is a key deliverable from this Program. Models of this type will also benefit future MOB and other related efforts in identifying technology shortfalls and pinpointing where best to apply technology advancement resources to most significantly improve system reliability and mission performance.

3.2.3.1 Advancements

Bechtel National, Inc. developed an Operational Availability (Ao) model capable of statistically evaluating multiple performance parameters of different MOB concepts to estimate the percentage of time that the MOB can perform a given mission. The model, named the MOB Performance Assessment Tool (MPAT), is believed to be the first use of a physics-based reliability model and simulation tool using actual metocean data inputs (Figure A-9). The simulation model was developed using Extend modeling software from Imagine That Inc. The model addresses MOB performance on the basis of mechanical, electrical, and structural reliability of the platform and its subsystems. But unlike traditional reliability models, MPAT also evaluates performance parameters against environmental effects and mission requirements.

The guiding basis for the calculations is a database containing 23 years of metocean data from 22 sites around the world (see Figure A-10). The database entries consist of wind, wave, and current descriptors (such as velocity, direction, significant height, mean period) averaged over 6 hour periods. A second key input to the MPAT model is the seakeeping database; those entries are precomputed using a hydrodynamic model that calculates the motions of the MOB and/or berthed vessels to waves over a range of incident directions and periods. A third set of necessary *a priori* inputs provides estimates of effective performance (such as net container off-loading throughput, or fuel for dynamic positioning thrusters versus current speed and direction) for components of interest (such as a particular crane model) to appropriate operational parameters (such as crane tip and/or vessel relative vertical motions). The final set of inputs provides repair times and probabilistic measures of operational reliability (mean time between failure) for key subsystems such as electrical generators.

The MPAT model then quantifies the overall system performance for a site and season of interest by examining discrete time intervals (e.g., several minutes) and accumulating those results. Specifically, MPAT applies the metocean conditions, gets associated dynamics of the MOB, vessels, runway, crane,

etc., determines if any key subsystems have (statistically) failed or are under repair, and then estimates various performance measures by correlating all of that to the performance data set. In this way the Ao model provides statistically reliable estimates of the real-world performance parameters such as cargo throughput, number of air sorties, and total fuel use. These can then be used to see if the mission requirements were satisfied, both in an overall context as well as other equally important measures such as maximum continuous up or down times. By modifying the databases the MPAT model is capable of efficiently simulating different designs and configurations of the MOB as well as different complex missions. For example, a mission may include one or two modules operating independently on site while other modules are in transit to the site, with all modules connected later in the mission to form a "full MOB" for some period of the operations (Figure A-11). The model accounts for performance during transit of modules as well as on-site operations.

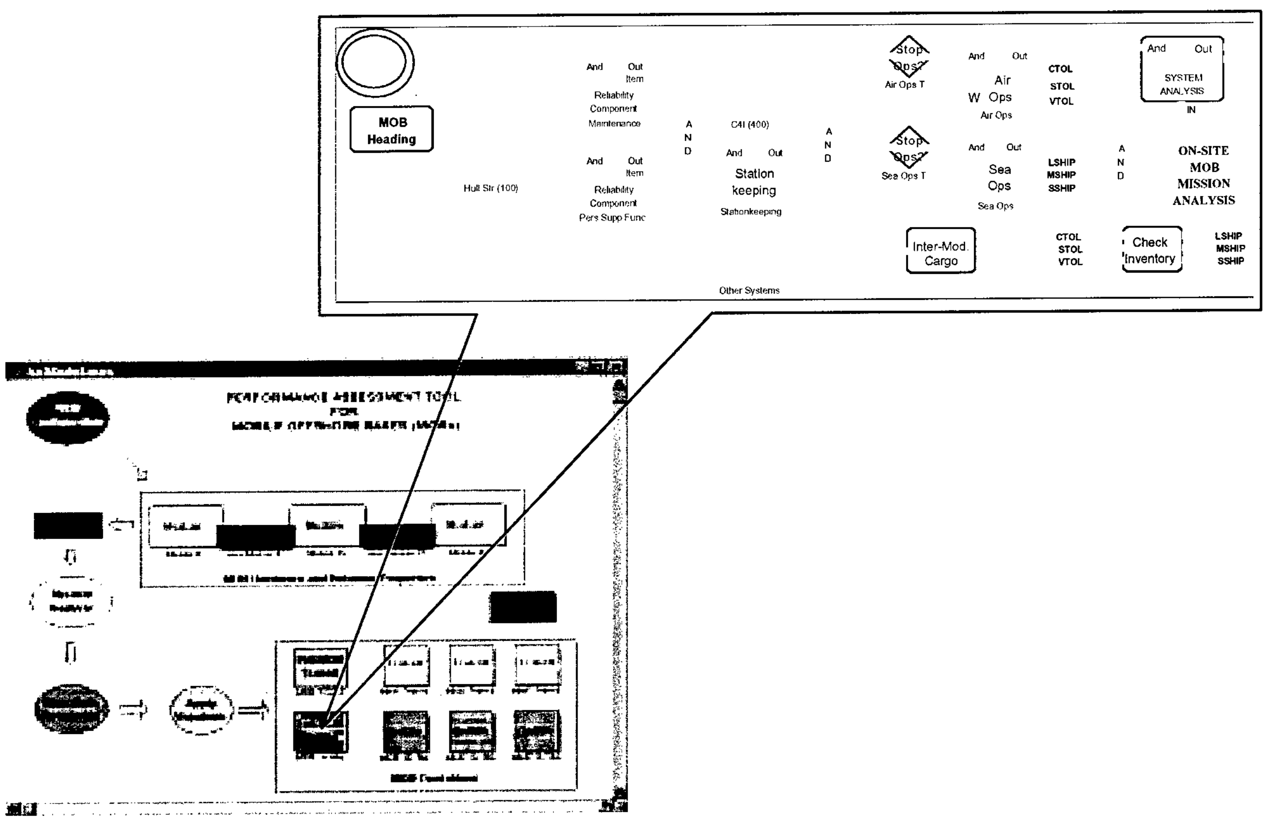

Figure A-9. Top and first level block diagram of MPAT simulation model.

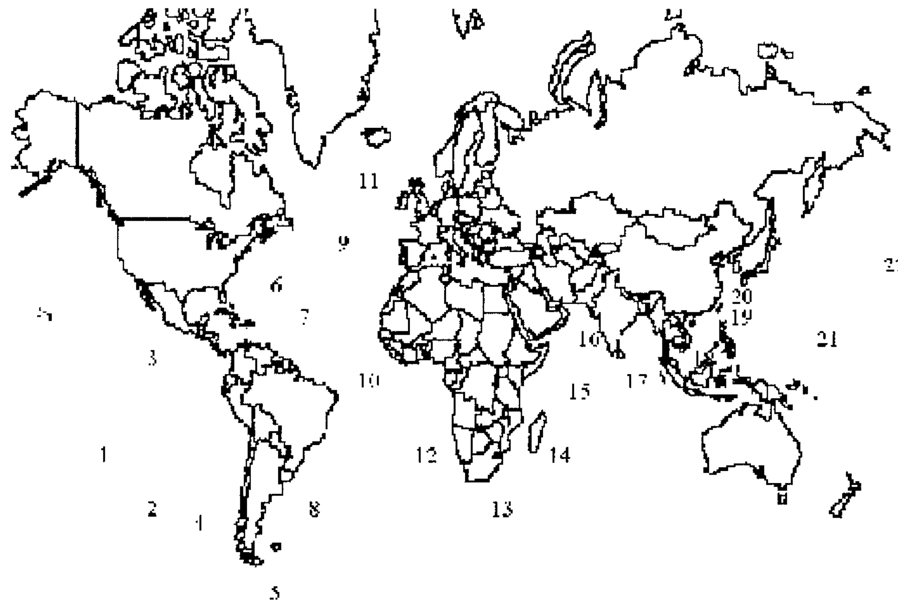

Figure A-10. Site locations for world wide database of historical metocean data.

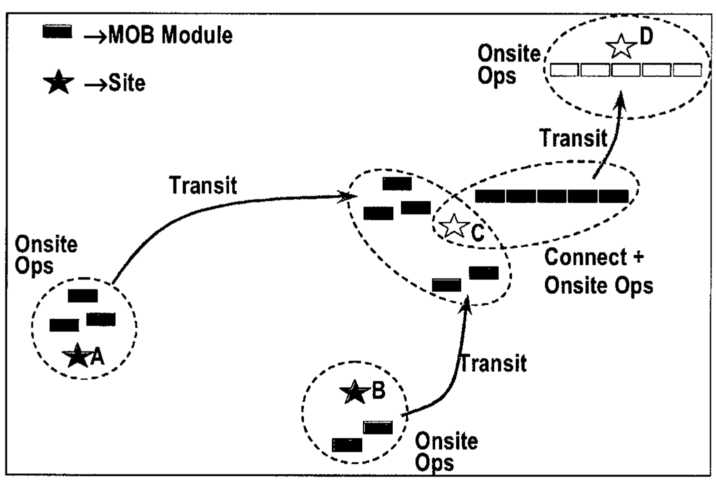

Figure A-11. Possible operations scenario diagram for MPAT simulation model.

The model allows evaluation of the performance of a given MOB configuration for a particular mission, as well as allowing statistical analysis of performance using the multiple years of environmental data. Output generated by the model includes operational availability statistics for the MOB as a whole as well as for critical sub-systems and operations, probability of mission success and statistics for the duration of particular mission events. Detailed time histories of important parameters such as weather, platform motions, or fuel use are also available in both graphical and data table formats.

This model integrates advancements from several other tasks conducted in this S&T program. It incorporates the results of the cargo transfer model developed by McDermott Technologies (this Appendix, Section 3.2.4, WBS 1.2.4), hydrodynamic and stability analyses as described throughout Appendix C, and capabilities of various cargo transfer hardware (this Appendix, Section 3.1.5, WBS 1.1.5). The model layout also was coordinated with the PASS design synthesis model (this Appendix, Section 3.2.2, WBS 1.2.2) and the ESWBS (Expanded Ship Work Breakdown Structure) as modified for MOB structures. This ensured that all key subsystems addressed in PASS for MOB-like structures were accounted for in the Ao simulation tool. The model was partially verified. Therefore it is not validated, nor has it been exercised for a full formal analysis of any MOB concept.

In addition to serving as a valuable performance evaluation tool, this model can also be used by designers to evaluate the sensitivity of overall MOB operational availability to changes in the reliability or availability of various subsystems by planners to simulate different operational scenarios. The model can identify critical operations and interfaces, and conduct cost-benefit trade-off studies to help determine where technology and design investment can most impact system reliability and mission performance. This model constitutes the most powerful performance evaluation tool developed in the program, and advances the general state-of-practice for reliability and performance modeling to a new level by integrating mechanical reliability, mission simulation, and actual environmental data for the first time.

3.2.3.2 Products

1. Bechtel National, Inc., MOB Performance Assessment Tool (MPAT). Operational Availability simulation models developed in Extend: AoModel.mox (model of 3-module MOB without connectors), AoModel2.mox (model of 5-module MOB with connectors), and Ao.lix (library of model blocks), December 1999.
2. Bechtel National, Inc., Operational Availability Assessment Model for MOBs, December 1999.
3. Jha, A.K., L.C. Lee, and R.C. Lundberg, Performance Assessment of Mobile Offshore Bases: Operational Availability and Probably of Mission Success Evaluation, Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99, Honolulu, HI, September 22-24, 1999, Volume I, pp. 238-248.

3.2.3.3 Resources

Bechtel National, Inc.

3.2.4 Cargo Transfer Rate Models (WBS 1.2.4)

McDermott Technology, Inc. was tasked to develop an analytically robust method for determining and comparing sea-based cargo transfer rates for different MOB configurations and cargo vessels. Tasking also included applying the model to cargo movements for several auxiliary ship types in multiple sea state and heading conditions. The purpose of the models was to evaluate the feasibility of conducting at-sea transfer operations from a MOB. The models can determine how rapidly performance degrades at the limits of operation, pinpoint steps in the cargo transfer process and equipment characteristics where technology advancement can provide the most benefit, and evaluate the payoff from incorporating different cargo handling mechanisms in a given MOB design.

3.2.4.1 Advancements

McDermott Technologies developed a suite of three analytical models (Figure A-12) for estimating cargo transfer rates for containers and Roll-On/Roll-Off (RO/RO) cargo between the MOB and a variety of vessels. Vessel-to-MOB container transfer operations (Figure A-13), and both vessel-to-MOB and MOB-to-vessel Roll-On/Roll-Off (RO/RO) operations (Figure A-14) are modeled. All models are based on the ARENA general-purpose modeling and simulation tool, and simulate cargo transfer using discrete-event simulation. The models use predicted MOB motions and cargo vessel motions, operating characteristics of the cargo crane or RO/RO ramp, and layout of the cargo vessel to estimate transfer rates. This work was integrated with other tasking to McDermott under the Design Tools product area, which supplied the MOB platform and vessel motions inputs (Appendix C, Section 3.1.5, WBS 3.1.5). This work also utilized information resulting from the NIST tasks on containerized cargo transfer technologies (Appendix A, Section 3.1.5, WBS 1.1.5).

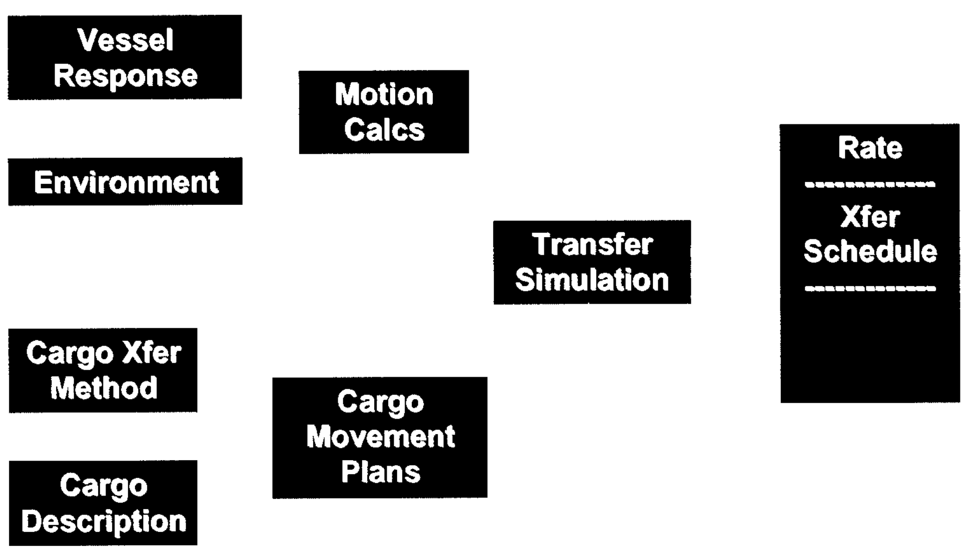

Figure A-12. Block diagram of Ship Cargo Transfer Rate Model.

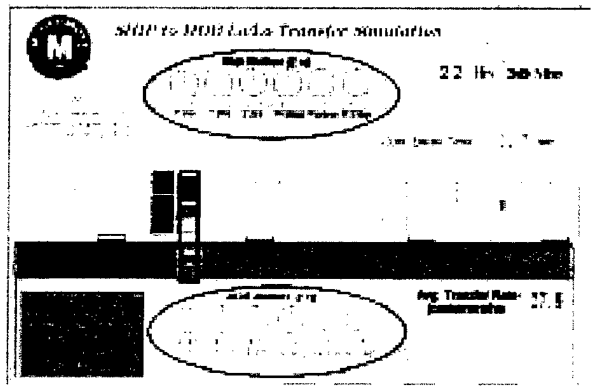

Figure A-13. Animation screen of LO/LO cargo transfer in Cargo Transfer Rate Model.

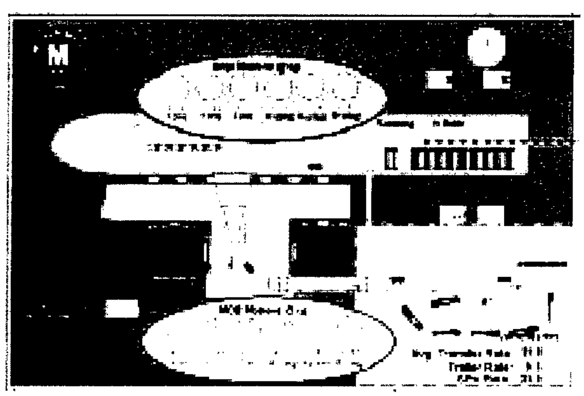

Figure A-14. Animation screen of RO/RO cargo transfer in Cargo Transfer Rate Model.

While the models are capable of performing stand-alone evaluations of transfer rates, they also provide direct input to the Ao model described in (WBS 1.2.3) Section 3.2.3 of Appendix A. The models can also be extended and integrated with other models to evaluate cargo operations in more detail. This tool provides a valuable method for evaluating the pay-off of including advanced cargo transfer systems in MOB designs.

The models were verified and validated with as much empirical data as McDermott could obtain during the development effort. The tools are somewhat simple in modeling human decision-making processes and the impacts of those decisions (regarding whether or not to initiate a container lift or begin crossing a vehicle ramp), resulting in overly-optimistic transfer rates for those cases including manual control. A more realistic modeling of the human decision making process and its results was recommended by both the Government and the developer for future work on the models.

Initial analyses completed in this effort have produced results indicating that open-ocean cargo transfer rates from ships in sea states up to Sea State 4 may suffer less degradation than previously thought. It must be noted, however, that for container movement these results were based on the predicted performance of computer-controlled transfer cranes and handling hardware still in the development phase. The critical parameters affecting these results are the ability of automated cranes to acquire and latch containers using high-tech spreader bar controllers and the ability to stabilize crane loads against wind and inertial forces. Despite the uncertainties of actual crane performance, results indicate that the mission-critical operation of open-ocean cargo transfer may be more feasible than initially expected. This would substantially enhance the feasibility of MOB operations overall.

3.2.4.2 Products

1. Cybulsky, M.K. and Richard Currie, Simulation as a Tool for Cargo Rate Determination, Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99, Honolulu, HI, September 22-24, 1999, Volume I, pp.229-237.
2. McDermott Technology, Inc., Generalized Sea Cargo Transfer Model Final Project Report, May 5, 2000.
3. McDermott Technology, Inc., MOB to Ship RO/RO cargo transfer rate simulation mode in Arena Viewer: MOBtoSHIP_RoRo_Rev1, May 5, 2000.
4. McDermott Technology, Inc., Ship to MOB LO/LO cargo transfer rate simulation model in Arena Viewer: SHIPtoMOB_LoLo_Rev1, May 5, 2000.
5. McDermott Technology, Inc., Ship to MOB RO/RO cargo transfer rate simulation model in Arena Viewer: SHIPtoMOB_RoRo_Rev1, May 5, 2000.

3.2.4.3 Resources

McDermott Technologies, Inc.

3.2.5 Constructability Models and Assessment (WBS 1.2.5)

Because MOB modules are several times larger than any ships or semisubmersibles that presently exist, conventional construction practices and facilities may not be capable of building them, or at best, building them inefficiently. At the beginning of the S&T program it was unclear whether or not the U.S. offshore construction and shipbuilding industries had the capacity (in terms of facilities, labor, transportation, and raw materials), to actually construct one or more MOB modules in a reasonable time frame.

The University of Maryland was tasked to develop a method for assessing the construction feasibility of alternative MOB concepts using existing risk-based procedures to evaluate the risks and costs associated with different construction strategies for MOB modules. Tasking also included:

1) Evaluating the constructability of five different MOB concepts developed to date in the S&T program.
2) Developing a set of preliminary constructability guidelines for MOB.
3) Investigating the construction of MOB modules from a terrestrial-based facility (as opposed to afloat assembly), and
4) Assessing the impact of weather on construction operations.

3.2.5.1 Advancements

The University of Maryland established, documented, and applied a risk-based method for evaluating the constructability of the MOB. A comprehensive baseline of the U.S. shipbuilding and offshore construction industry capability to build a MOB was established, and an assessment of the constructability of each of five MOB concepts advanced in the S&T program was completed. Independent construction cost and schedule estimates have been developed for the five concepts, with the construction of each concept modeled and simulated using two different construction strategies. The first strategy addressed construction of the modules ashore and the other strategy simulated afloat construction. The effort focussed on the construction of the platform hulls for MOB concepts, as these pose the biggest challenge to the industry. A risk assessment for the construction of a MOB was integral to the evaluations, addressing the issues of adequate capacity in terms of facilities, materials, labor, transportation, but also considering the construction risks and impacts to cost and schedule associated with construction management strategies, environmental regulation, and safety.

This work advanced some innovative techniques for modeling construction and accounting for construction risks. For example, construction management issues were modeled using an application of fuzzy logic principals. Insights gained from the risk assessment and constructability evaluations were documented in a set of preliminary constructability guidelines for MOB. This work also included a deeper study of constructing MOB modules from special land-based facilities, which could lead to lower total life cycle costs for a MOB since the facilities would allow less expensive land-based maintenance operations when compared to work afloat. The impact of weather effects on component transportation and offshore assembly also was addressed as part of this overall task.

The results of this work have directly improved the understanding and feasibility of constructing a MOB, providing a quantitative assessment of the feasibility of construction. Although focussed on MOB modules, the techniques used in this study are directly applicable to other large offshore or terrestrial

construction projects. This task also has shown that the U.S. shipbuilding industrial base can build a MOB in a reasonable time frame and could probably support competitive bidding.

3.2.5.2 Products

1. Ayyub, B.M. and W.J. Bender, A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base Part I: Risk-Informed Assessment Methodology, University of Maryland Center for Technology and Systems Management, 2 February 1999.
2. Ayyub, B.M., W.J. Bender, A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base Part II: Construction Systems Definition, University of Maryland Center for Technology and Systems Management, 28 May 1999.
3. Ayyub, B.M., W.J. Bender, A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base Part III: Construction Risk Analysis, University of Maryland Center for Technology and Systems Management, 21 July 1999.
4. Ayyub, B.M., W.J. Bender, A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base Part IV: Preliminary Constructability Guidelines", University of Maryland Center for Technology and Systems Management, 13 December 1999.
5. Ayyub, B.M., W.J. Bender, A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base Part V: Special Topics: Terrestrial Construction, Weather Risk Analysis, University of Maryland Center for Technology and Systems Management, 24 July 2000.
6. Bender, W.J., B.M. Ayyub, and A.N. Blair, Assessment of the Construction Feasibility of the Mobile Offshore Base", <u>Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99,</u> Honolulu, HI, September 22-24, 1999, Volume II, pp. 699 - 707.
7. Blair, A.N., BM. Ayyub, and W.J. Bender, Fuzzy Stochastic Cost and Schedule Risk Analysis: MOB Case Study", <u>Proceedings of the 3rd International Workshop on Very Large Floating Structures VLFS '99,</u> Honolulu, HI, September 22-24, 1999, Volume II, pp. 733 - 742.
8. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Concrete and Steel Concept, Afloat Construction Scenario: Concreteafloatwcost.mox, July 1999.
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13. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Afloat Construction Scenario, including Weather Risk Analysis: HingedafloatWeatherRisk.mox, May 2000.
14. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Largest Module, Special Terrestrial Assembly Method: Largestspassemblymeth.mox, April 2000.
15. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Largest Module, Special Terrestrial Assembly Method, Dry Dock Assembly Only: Largestspassemblymethonlydrydock.mox, April 2000.
16. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Terrestrial Construction Scenario: Hingedterrestrialwithcost.mox, July 1999.
17. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Typical Module, Special Terrestrial Assembly Method: Typicalspassemblymeth.mox, April 2000.
18. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Hinged Concept, Typical Module, Special Terrestrial Assembly Method, Dry Dock Assembly Only: Typicalspassemblymethonlydrydock.mox, April 2000.
19. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Independent Module Concept, Afloat Construction Scenario: IndyafloatwithcostR1.mox, July 1999.
20. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Rigid Concept, Afloat Construction Scenario: Rigidafloatwithcost18July99.mox, July 1999.
21. University of Maryland Center for Technology and Systems Management, Simulation Model in Extend for Construction of Rigid Concept, Terrestrial Construction Scenario: Rigidterrestrialwithcost.mox, July 1999.

3.2.5.3 Resource

The University of Maryland, Center for Technology and Systems Management.

4 RECOMMENDATIONS

The following tasks are recommended to wrap up the advancements needed in the Requirements Definition and Performance Measures area of the existing Science & Technology program as the program transitions towards a demonstration phase.

4.1 Mission Requirements

4.1.1 Mission Definition and User Involvement

MOB development has been based on the 1995 MNS, which was never formally approved through the Joint Requirements Oversight Council (JROC) process. The MNS included a few missions, but was mostly prescriptive in nature. Although it is understood that the shifting nature of world politics and military development make it difficult to develop a precise performance document, greater involvement in the development process by official representatives from the user community will improve the quality of cost estimates and improve the focus of technical development.

4.1.2 Definition of Vessel Repair and Maintenance Requirements at MOB

One role for the MOB that has not yet been explored is that of serving as a replacement for the tenders that are being eliminated from the fleet. Because some of the capabilities required of a tender may have significant impact on a MOB, a derivation of requirements associated with this particular mission element would be valuable in rounding out the requirements definition for MOB missions.

4.1.3 Parametric Analysis of Airfield Dimensional Requirements with Changes in Operating Parameters

To more adequately illustrate the operational payoff, system cost and technical requirements associated with various airfield lengths, it is recommended that a parametric analysis of airfield dimensional requirements be conducted. Payload and range of various aircraft should be varied along with other operational and environmental parameters.

4.1.4 Improve Functionality of Hierarchical Database

Some minor improvements to the hierarchical database of mission requirements are recommended to improve its usefulness to any future MOB programs, as well as for the general use of the logistics community. They include:

- Adding the ability to compile all requirements for a given set of mission elements into a single printable and/or file output
- Providing an internal check to ensure that functional requirements are not duplicated when two or more mission elements are supported by one or more of the same functional requirements
- Adding the ability to trace functional requirements back to the driving capability and mission element, and
- Updating inputs to ensure that all new requirements derived over the past year of the S&T

Appendix B - Table of Contents

Standards and Criteria

Appendix B - Table of Figures

Standards and Criteria

Appendix B

Standards and Criteria

1 OVERVIEW

1.1 General Description

The objective of the Standards and Criteria product area was to develop a Mobile Offshore Base (MOB) Classification Guide addressing structural safety and integrity. This product area had two primary thrusts: Standards, which is the development of a reliability- and probabilistic -based framework for the Guide, and Criteria, which quantifies key parameters in the Guide such as the environmental specification/design basis, partial safety factors, and fatigue criteria.

Under the Standards subtask (WBS 3.1), this Program worked with the American Bureau of Shipping (ABS) to extend existing offshore practice and standards as well as integrating military standards where appropriate into a MOB Classification Guide. This Guide is among the first to introduce performance and risk-based requirements in the US offshore industry and is expected to help promote competition in the industry. Development of standards for novel and high-valued offshore structures in the future is likely to follow this lead. The Guide also includes a Commentary published in a separate volume. The purpose of the latter document is to provide justification and supporting information for the material presented in the Guide. The latest version of the Guide has three parts covering twenty-seven sections. While still incomplete, this is the primary technical deliverable from this MOB S&T Program.

The development of a MOB Classification Guide was executed by ABS. ABS officially publishes both Guides and Rules for commercial ships and offshore structures, and is the exclusive classification society for U.S. government ships and offshore structures. Guides are viewed as drafts or preliminary standards, which are on track towards later becoming Rules. The purpose of the MOB Classification Guide is to specify requirements for the design of the MOB and to provide design guidance on how these requirements may be met. Also, those responsible for certifying that the design is adequate will use the Guide. In terms of scope, the emphasis was on aspects associated with overall behavior, and in particular, aspects that are unique to MOB. In this regard the MOB Classification Guide addresses the following:

- functional, operational and logistics requirements
- structural integrity
- criteria (e.g., survivability and fatigue)
- stability performance
- maintainability
- dynamic positioning
- environmental compliance

Development of the MOB Classification Guide was evolutionary and remains a work in progress. It was advanced with the participation of DoD agencies (e.g., NFESC, NAVAIR, NAVSEA, and NSWC-CD) and industry (e.g., Bechtel National, Inc., Band Lavis, Inc., SYNTEK, Inc., and MCA Engineers, Inc.). Typically, Guide development is evolutionary in character and tends to codify past history and existing industry practice. But MOB is such a novel engineering system that this traditional approach was, on its own, inadequate. It was recognized from the start that it would be necessary to address several fundamental issues during development of this Guide and incorporate the best of existing practices when appropriate.

The primary emphasis within the Criteria subtask (WBS 3.2) was to develop a sufficiently complete environmental specification of wind, waves, and current at the unprecedented scale of the MOB that would later be used to form a MOB environmental design basis. This was necessarily a very comprehensive study that had two main thrusts. The first resulted in one report and two databases of wind, waves and currents numerically generated using hindcast models for 20 sites around the world. This package summarizes the engineering state-of-the-art for modeling meteorological and ocean ("metocean") conditions of wind, waves, and current. As detailed in Appendix B, Section 2.2.1, it includes all relevant phenomena, such as internal waves and solitons, and spans all conditions from mild fatigue to extreme survival during typhoons/ hurricanes. While some gaps remain, particularly in the joint vector descriptions of extreme events, this package represents a major advance in metocean specifications.

The second part of the environmental specification development consists of a coordinated series of pioneering studies aimed at understanding one of the largest uncertainties in the environmental specification – namely, wave spatial coherence at the one-mile scale of MOB platforms. The one-mile length of MOB platforms is unprecedented and creates new design challenges for marine structural analysts. The extreme length, coupled with a relatively narrow beam and draft, makes typical MOB platforms particularly susceptible to large torque and horizontal bending loads for near beam-on, two dimensional (e.g., infinite crest length) incident waves. It is known that these loads will reduce significantly for short crested waves; the key problem is that waves had never been investigated over the spatial scales appropriate for MOB platforms.

The Office of Naval Research sponsored a two-day workshop on the spatial coherence of surface ocean gravity waves in Arlington, Virginia on 19-20 August 1997. The purpose of the workshop was to explore whether the scientific understanding of the spatial coherence structure of ocean wave fields and/or available data was adequate for evaluation of conceptual MOB platforms. Findings from this workshop were published in an ONR summary report (available at the MOB web site). The workshop concluded that:

1) There were few measurements of sea surface coherence at the scale appropriate to a MOB.
2) Existing numerical and theoretical wave models were two dimensional, asymptotic and untested.
3) Laboratory basin studies would be helpful to the extent that field observations could confirm the fidelity of scaled simulations.
4) Emerging technologies in remote sensing and numerical simulation now offered the opportunity to address the coherence problem in a fundamental way inexpensively.

The studies of wave coherence (or shortcrestedness, or crest/trough length) were coordinated and partially funded through ONR Code 321 (Coastal Dynamics. Nine contracts and grants were awarded during summer 1998, and collectively they form this second thrust under MOB Criteria. Sections 2.2.2 through

2.2.9 of this appendix highlight the individual performers and technical advancements. Viewed collectively, the grants and contracts span three technical categories:

1. *Investigation using available wave data sets:*

   1.1 Measurements and analysis of waves in hurricanes (scanning radar altimeter (SRA) data via NOAA)

   1.2 Analysis of satellite wave measurements (synthetic aperture radar (SAR) data; two contracts)

   1.3 Analysis of wave array data (14 wave staffs in Lake Erie)

2. *Evaluation of signal processing techniques*

   2.1 Bispectrum

   2.2 Wavelets

3. *Physics-based modeling of waves*

   3.1 CFD modeling of waves

   3.2 Green-Naghdi equations for waves

   3.3 Inverse Scattering Transform and the nonlinear Shroedinger Equation

These grouping presents the three complementary objectives associated with this research:

1. Preliminary quantitative estimates of wave coherence based on direct analysis of available data.
2. Evaluation of signal processing techniques for quantifying coherence and wave crest lengths.
3. Evaluation of physics-based modeling techniques for the analysis and/or synthesis of three-dimensional ocean wave fields, as measured by their agreement with data from the wave data sets.

As with all pioneering work, there is no lack of fundamental questions associated with these studies. This can be clearly demonstrated with an example. Assume for illustrative purposes that a "perfect" snapshot of the ocean surface was available - with a suitable resolution (say, 5-10 m), and a mile scale. The goal is to "quantify the wave characteristics" – in particular, crest length – and, if possible, to ultimately identify what parameters best govern those characteristics (e.g., wave period, directional spread, etc.). But the wave analyst faces an immediate dilemma: what defines "a wave"? What if there is one long crest, yet two distinct troughs before or after it – is that one wave or two? Surprisingly, even the human eye has trouble differentiating if two random waves are "the same" or distinct; creating mathematical equivalent rules is even more challenging. There is still no present consensus as to the definition of "a wave", although trial definitions were assessed by the researchers.

The collective conclusions from this first round of wave coherence studies are impressive; ONR's assessment was that "The progress in the first year far exceeded what we had expected in two." Yet the results are unquestionably preliminary and incomplete. Some of the key advancements to date are summarized below:

1) One Scanning Radar Altimeter data set includes measurements of seven of the eight octants

in the Hurricane Bonnie wavefield – which is the first time a complete representative wavefield has been measured in a tropical storm. See Appendix B, Section 2.2.2.

2) Two studies have demonstrated that data from Synthetic Aperture Radar (orbital scanners) are sufficiently accurate over large swatches of the ocean for use in these coherence studies.

3) Multiple studies addressed whether linear or nonlinear simulations were required to correctly capture the statistics of ocean wave fields. Those results are mixed.

4) Three physics-based models that are capable of simulating large-scale wave fields were developed and partially validated. Rogue waves were included in the studies with promising results. However, much work remains to access their general accuracies and practical utility as part of the MOB Criteria development.

Several of the studies attempted to directly quantify crest lengths at the large MOB scale without benefit of a physics-based underlying model; this would provide immediate input to MOB designers while more fundamental studies continued. As stated above, the conclusions to-date are mixed so further studies are needed.

Even if these initial studies had succeeded in accurately quantifying crest lengths for all open ocean conditions, a third and final effort to develop a MOB environmental design basis is needed. This is necessary to identify how to intelligently reduce the infinite number of combinations of wind/wave/current/internal waves/solitons from any specification down to the minimum number of design cases that still adequately reflect expected ocean conditions. Without such guidance contained in the MOB Classification Guide and Commentary, the vastness of the environmental information will be too overwhelming to aid either designers, classifiers, or government acquisition engineers. Unfortunately, the short duration of this S&T Program precluded any significant progress on this last step. Appendix B, Section 2.1.1 has further discussions on this topic, particularly the section on Modern methods for identifying maximum response.

Further recommendations for the future Standards and Criteria development for MOB are listed in Section 4 of this Appendix.

1.2 Quality Assurance

The development of the Classification Guide was executed by ABS under direct contract with ONR. A MOB Standards and Criteria Working Group was formed to review progress bi-monthly during the evolution of the Classification Guide, which occurred during a period of two years between FY97 and FY99. The group was evenly constituted of government and industry representatives, all of whom were engineers. Members of the group are listed in the following table.

1.2.1 Standards and Criteria Working Group

Name	Organization
Al Ang	A.H-S. Ang and Associates 3 Centaurus Irvine, CA 92612
Bilal Ayyub	Dept. of Civil Engineering U. of Maryland College Park, MD 20742
Warren Baker	NAWC/AD Aircraft Division Lakehurst, New Jersey 08733
Roger Basu	ABS-Americas 16855 Northchase Dr. Houston, TX 77060-6008
Max Cheung	MCA Engineers, Inc. 2960 Airway Ave, #A-103 Costa Mesa, CA 92626
Judy Conley	Carderock Division Naval Surface Warfare Center 9500 MacArthur Blvd. West Bethesda, MD 20817
Allen Engle	Carderock Division Naval Surface Warfare Center 9500 MacArthur Blvd. West Bethesda, MD 20817
Nat Nappi, Jr.	NAVSEA 2531 Jefferson Davis Hwy. Arlington, VA 22242-5160
Tom Packard	NAVSEA 2531 Jefferson Davis Hwy. Arlington, VA 22242-5160
Stuart Pawsey	Bechtel National Inc. 333 Market St, 15 Fl. San Francisco, CA 94119-3965
Bill Richardson	Carderock Division Naval Surface Warfare Center 9500 MacArthur Blvd. West Bethesda, MD 20817

Gunnar Rognaas	Aker Maritime Tjuvholmen P.O. Box 1358 Vika N-0113 Oslo, Norway
Ted Shugar (Chair)	NFESC, Code ESC62 1100 23rd Ave Port Hueneme, CA 93043-4370

1.2.2 Wave Coherence Working Group

A Wave Coherence working group was also organized, with members consisting of the investigators funded to study wave coherence. This group met semiannually during the MOB Technology Exchange Conferences. Membership in this working group includes:

Name	Organization
Dr. Linwood Vincent	Chair, Office of Naval Research Code 321
Dr. Paul Palo	Co-chair, Naval Facilities Engineering Service Center
Dr. Leon Borgman	L.E. Borgman, Inc. (with NASA/Ed Walsh)
Dr. Mark Donelan	University of Miami
Dr. Steve Elgar	Woods Hole Oceanographic Institute
Dr. Cenzig Ertekin Dr. Jang Whan Kim	University of Hawaii
Dr. Frank Herbers	Naval Postgraduate School
Dr. Frank Monaldo	Johns Hopkins University Applied Physics Laboratory
Dr. Al Osborne	University of Torino (Italy)
Dr. Gene Terray	Woods Hole Oceanographic Institute
Dr. David Walker	ERIM International Inc
Dr. Ed Walsh	NASA/Goddard Space Flight Center
Dr. Dick Yue	Massachusetts Institute of Technology

1.2.3 Metocean Working Group

An informal Metocean Working Group met briefly during the development of the Environmental Specification described in WBS 2.2.1. This group is comprised of the members shown in the table below.

Name	Organization	Expertise
Dr. Allin Cornell	Stanford University	Probability Theory
Dr. Leon Borgman	L.E. Borgman, Inc.	Wave Statistics
Dr. Mark Donelan	University of Miami	Waves
Dr. Rob Pinkel	Scripps Institute of Oceanography	Internal Waves
Dr. Emil Simiu	National Institute of Standards and Technology	Wind
Dr. Bob Weller	Woods Hole Oceanographic Institute	Surface Currents
Dr. Jun Zhang	Texas A&M University	Extreme Waves

2 TECHNICAL ADVANCES

2.1 Key Issues

The largest Mobile Offshore Base would be several times larger than current open ocean platforms because of the requirement to accommodate landing and takeoff of large C-17 cargo aircraft. This introduces a variety of uncertainties associated with design related to this unprecedented size. Uncertainties relate to the specification of extreme ocean waves over a 1-mile scale, failure modes for very long, connected structures, accuracy of numerical simulation models for such large complex structures, life span integrity; hydrodynamic stability of connected modules, and structural integrity.

The MOB *Classification Guide* will be based on commercial standards supplemented by certain DoD and Navy ship requirements (e.g., explosive safety, survivability, damage stability, etc.). Various ABS Rules exist for commercial ships such as Steel Vessels and Small Water Plane Area Twin Hull (SWATH) vessels, and for moderately large floating offshore structures such as Mobile Offshore Drilling Units (MODUs). However, the unique functions, configuration and size of MOB renders existing classification rules inadequate by themselves for certifying a very large floating structure (VLFS) such as a MOB.

2.2 Major Products

The two tables in this section provide a comprehensive list of specific tasks associated with the Standards and Criteria product area. Their significance to MOB as well as to advances in industry capabilities is included. Each of these tasks is detailed in Appendix B, Section 3 according to WBS identifier.

2.2.1 Standards Subcategory (WBS 2.1)

WBS	Task	Advancement
2.1.1	*MOB Classification Guide* and *Commentary*	Structural design and approval basis for MOB
2.1.2	Independent Review Team for MOB S&T Program Office	Overall S&T Program quality assurance
2.1.3	Reliability-Based Fatigue Design Demonstration	Dry-run fatigue design demonstration in a reliability framework for large ships
2.1.4	Fracture-Based Fatigue Design Procedure for MOB Connectors	Fundamental new model for fatigue that uses no empirical coefficients
2.1.5	Strength Models for MOB Classification Guide	Technology transfer of recent Navy developed LRFD strength models
2.1.6	Reinforced Concrete Materials for Hybrid MOB Concept	The case for a concrete hull for MOB to reduce maintenance cost
2.1.7	FPSO Technology Review	Investigation of largest connectors operating in open ocean conditions

2.1.8	Initial Validation of *MOB Classification Guide*	Dry-run application of evolving *Classification Guide*
2.1.9	Initial MOB Survivability Analysis	Prerequisite survivability studies of a MOB
2.1.10	MOB Explosive Safety Analysis	Initial Design Criteria for MOB Magazines
2.1.11	Concrete Material Specification for MOB	Navy-generated quality assurance requirements for marine concrete materials
2.1.12	Environmental Compliance for MOB	Design considerations for avoiding non compliance during construction and operation of MOB

2.2.2 Criteria Subcategory (WBS 2.2)

WBS	Task	Advancement
2.2.1	Environmental Specification Package	1. Metocean (wind/wave/current) Specification 2. Global Hindcast Database and Analysis Tool 3. Typhoon Hindcast Database and Tool
2.2.2	Spatial Coherence of Ocean Waves from Surface Scanning Radar Altimeter Data	Collect SRA data; estimate coherence and crest lengths using covariance- and spatial -based signal processing
2.2.3	Synthetic Aperture Radar (SAR) Measurements of Wave Coherence	Broad investigation of existing Space Shuttle SAR data regarding extraction of crest lengths (complimentary study to WBS 2.2.24).
2.2.4	Wave Coherence Measurements Using Synthetic Aperture Radar	Focused study to investigate the utility of satellite SAR data (complimentary study to WBS 2.2.23).
2.2.5	Observations and Modeling of Spatial Wave Coherence	Directional wavelet analysis using time series records from a 14 gage array in shallow water
2.2.6	Spatial Coherence and Crest-length Statistics of Waves In Deep Water	Simulate 3D sea states using target frequency-direction spectra and second-order nonlinearity; analyze synthetic wavefields using bispectrum.
2.2.7	Nonlinear Dynamics of Three-Dimensional Wave and Wave-Group Interactions – Direct Computations	Model the nonlinear interactions with a higher order spectral (HOS) model, and refine the kinematics of extreme waves with a mixed Eulerian-Lagrangian (MEL) model.

2.2.8	Spatial Coherence of Surface Waves by Nonlinear Green-Naghdi Model in Deep Water	Simulate synthetic sea surfaces with target directional spectra, quantify the spatial coherence modeled and compare to observations.
2.2.9	Modeling of Rogue Waves using the Nonlinear Shroedinger Equation	Numerical and analytical investigations of rogue waves using Inverse Scattering Transform (IST) for both unidirectional and one dimensional wave fields, and for two dimensional wave fields defined by directionally spread wave trains.

3 PRODUCTS DESCRIPTION

3.1 Standards Subcategory (WBS 2.1)

3.1.1 MOB Classification Guide and Commentary (WBS 2.1.1)

3.1.1.1 Advancements

The purpose of the *Classification Guide* is to specify requirements for the design of a MOB and to provide guidance and constraints on how these requirements must be met. Those responsible for certifying that the design is adequate also will use the *Guide*. In terms of scope, the emphasis is on overall behavior, in particular, aspects that are unique to MOB. The *Guide* addresses design requirements, design approach, environmental specification/design basis, strength, load computation and combinations, motion and response analysis, uncertainty analysis, fatigue, stability, reliability analysis and dynamic positioning. The scope and structure of the Guide is evident from the table of contents reproduced below and, in particular, Section C, Design Guidance:

A. GENERAL

- *A.1. Purpose*
- *A.2. Scope*
- *A.3. Organization of Document*
- *A.4. Role of Classification Guide in Design Process*
- *A.5. Definitions*
- *A.6. List of Symbols*
- *A.7. Abbreviations*
- *A.8. Referenced Material*
- *A.9. Units*

B. CLASSIFICATION REQUIREMENTS

- *A.10. Background*
- *A.11. General Requirements*
- *A.12. Specific Requirements*
- *A.13. Demonstration of Conformance and Documentation*

C. DESIGN GUIDANCE

- *A.14. Design Approach*
- *A.15. Environment*
- *A.16. Loads*
- *A.17. Global Response Analysis*

A.18. Fatigue and Fracture Analysis

A.19. Reliability Analysis

A.20. Stability Analysis

A.21. Structural Arrangement

A.22. Structural Resistance

A.23. Accidental Explosions

A.24. Maintenance and Inspection

A.25. Environmental Compliance Considerations

A.26. Dynamic Positioning

A.27. Additional Guidance

Because of its unprecedented nature, the design of MOB requires a more fundamental approach compared to that used for conventional marine structures. As a result, this *Guide* represents a significant advance over existing similar documents. In this regard some key features of the *Guide* are:

- reliability-based
- incorporates elements of performance-based design
- encourages a systems view of the structure
- includes modern methods of response prediction
- emphasizes structural integrity of connectors

The role of each of these is described below.

Reliability-based design. The practical implementation of reliability theory in design standards requires a number of simplifications. The most popular method of implementation is the partial safety factor approach (often referred to as Load and Resistance Factor Design or LRFD) where factors are applied to both load and resistance variables. Such methods have been successfully applied to fixed structures such as buildings, bridges and fixed offshore platforms. However, very little progress has been made with floating structures, primarily due to complexities associated with the coupling between the load and response of floating structures (these are decoupled with fixed structures). As part of the development of the Guide, methodologies were developed that can be employed to develop LRFD factors suitable for the design of MOB.

Performance-based design. Most design standards, codes, guides, etc. are *prescriptive* wherein design requirements are expressed in terms of quantitative criteria. For these cases if the "cookbook" criteria are met the design is deemed adequate. The relationship between criteria and performance is implicit. A key feature of prescriptive methods is that they are based on past experience.

In the case of MOB there is no past experience, so prescriptive approaches are undefined. Instead, a

performance-based approach is more suitable wherein performance targets are specified, and the designer is required to demonstrate that the targets have been met. A greater burden is thus put on the designer of MOB (and developers of the *Guide*) to view the process in a more fundamental way. Specifically, this encourages the designer to consider environmental design conditions and modes of failure that are relevant to MOB but which may not be for conventional marine structures.

Despite the remarks made above there is a role for prescription in the design of MOB. Prescriptive methods for local structural behavior are acceptable because at the local level behavior in MOB structure is effectively indistinguishable from that of other large marine structures. Hence, prescriptive-based design can be used at the local level to complement performance-based design at the global level.

Systems view of the structure. Most existing structural standards are element-based wherein demonstration of adequate behavior at the element (local, component) level is considered sufficient to ensure adequate performance at the global level. Such an approach is reasonable for structures with a history of successful performance. As discussed immediately above, MOB requires a more explicit consideration of system level behavior. While the MOB Guide is not the first such document to address these considerations it appears to be the first to address the issue to this depth and consistency. The Guide calls for the application of direct reliability methods as being most suitable for the assessment of system level behavior of MOB; this is in contrast to the relatively simple LRFD approach, which is recommended for element-level design.

The Guide also provides specific performance targets for ensuring safety against progressive collapse and also for ensuring adequate residual strength once the MOB has sustained substantial damage.

Modern methods for identifying maximum response. Identification of critical environmental conditions was recognized early on as a key challenge in the Guide development process. Two facts central to this were:

1) The maximum response does not necessarily occur under the most severe environmental conditions.

2) Different types of responses peak at different environmental conditions subject to the same probability of exceedance.

It was recognized early on that the numerous types of simulations associated with a MOB design (survival, fatigue, operational, and damage scenarios) and the high computational demands of each associated structural and hydrodynamic analysis were daunting. Those analysis requirements are unavoidable. It was further recognized that conducting a comprehensive set of probabilistic-based simulations that accounted for all likely joint, vector metocean excitations per scenario was unworkable. In other words, rules had to be developed to allow for intelligent downselecting of all possible analyses and metocean excitations into a *MOB environmental design basis* consisting of a manageable and representative set of critical cases. That task was not wholly completed. However, the *Guide* does recognize three candidate response-based approaches for identifying the critical environment instead of the more commonly prescribed phenomenon-based approach in which, e.g., the 100-year wave is prescribed as a design condition. Those methods are:

1) The method of response statistics: The statistical properties of the response in question are obtained from a large number of experiments (numerical or physical) by randomly generating environmental conditions for each set of experiments. This is computationally very demanding.

2) The cell method: The entire operating life of the vessel is split into mutually exclusive and collectively exhaustive set of "cells". By further assuming independence among events occurring within a cell, and then performing Monte-Carlo simulations, the response corresponding to a given probability of exceedance may be determined.

3) The environmental contour method (ECM): A contour corresponding to the required probability of exceedance is drawn in the plane of environmental variables. Environmental combinations only along this contour is then input to the response model, and the maximum response found this way is the design response. An attractive feature of the method is that environmental description and response analysis can be decoupled. The MOB team at ABS developed an important extension of ECM for adaptation to novel structures. This method was applied in a fully worked-out example of connector strength design in a hinged MOB concept.

Structural integrity of connectors. The inter-module MOB connectors are among the most critical elements for MOB. While some connectors are in use for floating marine systems (e.g., FPSOs and floating bridges), connector technology is underdeveloped and represents a high degree of technical risk to the MOB system. A key aspect of the structural integrity of connectors is their fatigue and fracture performance. Conventional guidance against fatigue failure of structural elements and joints is among the most prescriptive of all design methodologies. In virtually all such guidance the Miner-Palmgren hypothesis is used which relies on the existence of experimental data relating stress range and number of cycles to failure at that stress range and for the size of the relevant detail. The existence of such data cannot be assumed for MOB given the expected large scale of the connectors. Instead, an advanced fracture mechanics based methodology was included in the Guide for these critical analyses.

Risk reduction as a goal. In the development of the Guide there was the conscious effort to develop an approach, and methodologies, to minimize the risk associated with the engineering of novel and complex systems. The global response behavior of MOB is considered to be the most significant overall source of uncertainty, and therefore a concerted effort was made to include techniques that require the designer to thoroughly investigate response and failure modes that are unique to MOB. The Guide also provides target reliabilities for the design of all MOB structural components and subsystems in all relevant failure modes. Special attention was directed to identify unusual failure modes that are not normally considered in the design of conventional floating structures. The Guide thus serves to substantially reduce the level of risk in the engineering of MOB.

As explained in this section, the *Guide*'s chapters are in various stages of completion. It is nonetheless a start, and could be used to great advantage in its present state if needed. Target reliabilities are recommended and limit states for structural design are set forth. Initial uncertainty data is included, but must be substantially refined based on hydrodynamic test data and further analysis of the fidelity of analysis and design tools.

3.1.1.2 Products

1. ABS Americas, Commentary to Preliminary MOB Classification Guide, Technical Report: AA99018, Houston, December 1999.

2. ABS Americas, Preliminary MOB Classification Guide, Technical Report: AA99018, Houston, December 1999.

3. Bhattacharya, B, K-T. Ma, and R. Basu, Developing Target Reliability for Novel Structures: the

Case of the Mobile Offshore Base," Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds., R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 398-407, 1999.

3.1.1.3 Resource

ABS Americas, Houston, Texas.

3.1.2 Independent Review Team for MOB S&T Program Office (WBS 2.1.2)

The engineers in the following list were the independent reviewers of the S&T Program. They were carefully selected for their international standing in their respective areas of specialty. Three are members of the National Academy of Engineers, and all are recognized international experts in offshore engineering.

Independent Reviewer	Expertise
Al Ang, A. H-S., Ang and Associates	Reliability-Based Structural Design
Max Cheung, MCA Engineers, Inc.	Offshore Structural Design
Jim Garrison, Oregon State University	Computational Hydrodynamics
Joe Penzien, International Civil Engineering Consultants, Inc.	Offshore Structural Dynamics
Marshal Tulin, University of California Santa Barbara	Theoretical and Experimental Hydrodynamics

The reviewer's attended the semiannual MOB Technology Conferences, wherein each participant presented their advances. The Program Office carefully considered their submitted reports, which assessed progress throughout the review period, and where applicable, they were shared with program participants. Their participation was not simply limited to the conferences. They, along with others, reviewed all technical products during their development to ensure the highest quality products for the Program. In addition to providing written and verbal reviews of the Program's progress, team members had the opportunity to participate in the Program. When and where its members saw an oversight or gap in the technical program where they might be able to contribute, they were permitted to submit a proposal for an auxiliary study. In three cases the Program Office accepted these proposals and they resulted in small funded tasks, two of which were in the present product area (Standards and Criteria) and reported on below.

3.1.2.1 Products

1. MCA Engineers; each team member contributed four semi-annual trip reports for the records of the MOB S&T Program Office. These reports documented observations primarily from attendance at Semi-Annual MOB Technology Exchange Conferences.

3.1.2.2 Resource

Contract administered by MCA Engineers, Inc., Costa Mesa, California.

3.1.3 Reliability-Based Fatigue Design Demonstration (WBS 2.1.3)

3.1.3.1 Advancements

This study is an auxiliary special technical effort funded as part of the Independent Review Team's oversight responsibility. The two objectives were to:

1. Evaluate the applicability of a new reliability-based method for the fatigue analysis of welded joints that had been proposed for bridges and ship structures.
2. Recommend a feasible strategy for implementing the method into the *Guide.*

Fatigue lives of metal structures vary widely even under a constant-amplitude cyclic loading. In real applications, of course, the loadings would invariably be variable and random. For these reasons, and the presence of unavoidable uncertainties underlying engineering analysis and design, the assurance of fatigue life is realistically feasible only in terms of probability. In the proposed method the probabilistic reliability of a special welded joint of a metal structure is assessed for a given life (in number of cycles of repeated reverse loading) under a specified spectrum of stress-range amplitudes. The physics of structural fatigue is based on the conventional S/N technology of fatigue and Miners' rule for fatigue damage accumulation. All of this is embedded within a reliability framework, in which the scatter of fatigue lives about an S/N relationship is modeled by the Weibull probability distribution and random loading (i.e., applied stress-ranges) is modeled with the beta probability density function (PDF). The development of associated computer software constituted part of this study.

This work concluded that large commercial ships such as LNG tankers are underdesigned for fatigue. Their reliability was calculated at only about 0.8, considerably below what is desirable and what previous analyses had estimated. That is, the conclusion is that 20 of every 100 LNG tankers constructed will suffer fatigue failure. This low value is in fact consistent with in-service records for the subject class of vessel, which show fatigue damage that far exceeded the expectations. Industry has already acted, and at least one tanker under construction has been modified with additional structural steel in part due to this conclusion.

Through participation in this task the offshore structural design industry was introduced to reliability-based fatigue design technology. The success of this task and the conclusions reached were in part due to the analysis opportunity presented by the existence of a new data base of strain gage measurements that was developed by MCA Engineers, Inc. In addition, MCA was directly involved in the fatigue reliability analysis of LNG tankers.

3.1.3.2 Products

1. Ang, A.H-S, Technical Review Letter Report on Reliability-Based Fatigue Design, A.H-S. and Associates, Irvine, 20 December 1998.
2. Ang, A.H-S., M. C. Cheung, T. A. Shugar, and J. D. Fernie, Reliability-Based Fatigue Analysis and Design of Floating Structures, Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds, R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 375-380, 1999.
3. Ang, A.H-S., M. C. Cheung, T. A. Shugar, and J. D. Fernie, Reliability-Based Fatigue Analysis and Design of Floating Structures, Marine Structures Journal, in publication, 2000.
4. Department of Civil and Environmental Engineering, University of California, Irvine, Fatigue

Reliability Analysis Program (FRAP) Computer Program, 1998.

5. Hamilton, C., FRAP User's Manual, Department of Civil and Environmental Engineering, University of California, Irvine, 5 October 1998.

3.1.3.3 Resource

MCA Engineers, Inc., Costa Mesa, California and A. H-S. Ang and Associates, Irvine, California.

3.1.4 Fracture-Based Fatigue Design Procedure for MOB Connectors (WBS 2.1.4)

3.1.4.1 Advancements

The uniqueness and size of a MOB mainly drove the S&T Program design issues. This was no more evident than in the approach to design standards for MOB connectors. These connectors must transmit forces that are an order magnitude larger than the largest connectors operating in the open ocean today (see FPSO technology below). There is no experience with structural or fatigue design of such large connectors. The Standards and Criteria Working Group philosophy in such situations was to take first principles approach to design standards. Conventional fatigue design approaches are empirical (e.g., S/N curve approach, Minor's rule, etc.), requiring a large experimental database for support. Yet, we expect that a MOB connector will be constructed of large steel plate sizes for which requisite experimental data of the conventional type do not exist. It is not likely such data would be forthcoming due to prohibitive costs associated with extension of conventional fatigue testing to large structural scales.

Given this situation, first principles approach to fatigue design of MOB connectors was taken. In this case, a fracture mechanics based methodology was pursued. Fortunately, the approach has been successful and has culminated in a new fatigue crack growth rate law that is apparently very accurate, as measured by its success in matching 38 of 38 sets of published experiment data on a variety of metal alloys. The resulting theory has the singular advantage of being an entirely analytical formulation, based entirely on conventional material properties including, for example, steel's fracture toughness. No empirical coefficients are involved. Therefore, in contrast with existing empirical fatigue propagation laws, there is no inherent obstacle to its application to full scale structures.

The new fatigue crack growth rate law has been judged to be an improvement on existing models by one recognized authority in fracture mechanics. With one equation, it unifies all three regions of the classical compound curve for crack growth rate in metals. Further, because it is an entirely analytical result, it promises a more elegant solution procedure for fatigue design problems than that currently offered by empirically based models. It has been introduced to an international community of metal fatigue researchers, with the result that it has generated interest and or requests from representatives of the academic community, the commercial finite element industry, NASA, and the Navy at ONR and NRL. Two papers describing the model and its extension to corrosion environments are currently in review by the *International Journal of Fatigue*. Additional research is needed for a fuller appreciation of the model's performance, and further experimental validation is warranted with both repeated stress fatigue data and corrosion fatigue data on metal alloys.

3.1.4.2 Products

1. Ramsamooj, D.V., Fracture Mechanics Fatigue Design of MOB Connectors, Contract No. 300034, MCA Engineers, Inc., Oxnard, CA, 11 August 1999.
2. Ramsamooj, D.V., MOBYDICK Computer Program (see Ramsamooj, D.V., Fracture Mechanics Fatigue Design of MOB Connectors, Contract No. 300034, MCA Engineers, Inc., Oxnard, CA, 11 August 1999).
3. Ramsamooj, D.V. and T.A. Shugar, Fatigue Crack Growth in Inert Environment, International Conference on Fatigue Damage of Structural Materials, Hyannis, MA, 17-22 September 2000.
4. Ramsamooj, D.V. and T.A. Shugar, Fatigue Crack Growth in Aggressive Environment, International Conference on Fatigue Damage of Structural Materials, Hyannis, MA, 17-22 September 2000.

5. Ramsamooj, D.V. and T.A. Shugar, Prediction of Fracture-Based Fatigue Life of Connectors for the Mobile Offshore Base, Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds, R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 660-669, 1999.
6. Ramsamooj, D.V. and T.A. Shugar, Reliability Analysis of Fracture-Based Fatigue Life for Mobile Offshore Base Connectors, Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds, R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 367-374, 1999.
7. Ramsamooj, D.V. and T.A. Shugar, Reliability Analysis of Fracture-Based Fatigue Life for Mobile Offshore Base Connectors, Marine Structures Journal, 2000.

3.1.4.3 Resource

D. V. Ramsamooj, California State University, Fullerton.

3.1.5 Strength Models for MOB Classification Guide (WBS 2.1.5)

3.1.5.1 Advancements

Uncertainty data pertaining to structural design parameters is crucial to the development of reliability-based standards. Development of uncertainty data such as means and standard deviations for design parameters and novel structures is an expensive proposition. The Guide is required to contain such information for support of its procedures and recommendations, and indeed, independent reviews of intermediate revisions of the Guide contained comments to the effect that such information was conspicuous by its absence. Yet, development of such data was beyond the scope of ABS's contract for producing the Guide.

It happened that the Navy had already developed and continues to develop substantial uncertainty data for proposed reliability-based design standards of surface combatants. These design data were obtained at considerable expense. The MOB Standards and Criteria Working Group believed that some of it was applicable to the reliability-based Guide. This task is a classic example of technology transfer; in this case, uncertainty data associated with prediction models for strength of structural members developed by the Navy for surface combatants was passed to ABS for use in the Guide. In fact, this information regarding design of structural elements such as plates and frames provides the only prescriptive-based requirement in the MOB Classification Guide as described under Performance-based design in Appendix B, Section 3.1.1. This uncertainty data is described and documented in the following publication:

> Melton, W.M. and R.M. Ayyub (1999). "LRFD Rules for Naval Surface Ship Structures: Reliability-Based Load and Resistance Factor Design Rules," Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-65-1998/4, December 1999.

Both ABS and NSWC/CD, with the recommendation of the Standards and Criteria Working Group, accepted the idea that this transfer of technology was in principle mutually inclusive of their interests. All concerns for accessibility, accuracy, and appropriateness to MOB were met during extensive review and discussion of the data and in negotiations with ABS and NSWCCD. The data is for use by ABS for generation of MOB-related standards exclusively. As a result of this task, at least some of the requisite uncertainty data for reliability-based design of a MOB is contained in the Guide. Though much more uncertainty data that is specific to MOB, needs to be acquired, this initial installment serves to activate the Guide as a preliminary design document supporting any potential MOB design program.

3.1.5.2 Products

None (incorporated into *Guide*).

3.1.5.3 Resource

R.M. Ayyub, University of Maryland, and Naval Surface Warfare Center, Carderock Division.

3.1.6 Reinforced Concrete Materials for Hybrid MOB Concept (WBS 2.1.6)

3.1.6.1 Advancements

The objective of this task was to evaluate the use of concrete as an alternative material for the design of a semisubmersible hull for a MOB. It was termed the Phase 2 Study, since it was a follow-on study to Aker Maritime's concept configuration design study, which is termed the Phase 1 Study. The Phase 1 Study produced a concept called the Concrete/Steel Hybrid MOB. It is a four-module concept in which each module has steel topsides and a concrete semisubmersible lower hull (pontoons and columns).

The present Phase 2 Study addressed concrete materials for a generic semisubmersible hull design. The focus of this study was on concrete irrespective of the basic concept configuration for a MOB. It addressed four key questions:

1) What is the appropriate concrete mix design?
2) What is the appropriate structural concrete design?
3) What is the appropriate construction method?
4) What is the life cycle cost?

The preliminary design of a hybrid MOB (Phase 1) is described in Appendix D, Section 3.1.4. Aker Maritime has extensive experience in construction of large monolithic floating structures that in size are comparable to a MOB module. As an example, the concrete substructure for the Troll A platform has a total height of 367 meters which is comparable to the length of one hybrid module, 380 meters.

For this Phase 2 task, after extensive study Aker concluded that concrete was acceptable for a MOB and would provide a hull that could easily achieve a required 40- to 50-year life span with minimal maintenance. Aker also described the construction sequence of a concrete hull for the MOB based on experiences for platforms like Troll. The construction may either be performed by increasing the capabilities of current dock facilities or by establishing a "construction assembly line". The latter method is also well proven and tailored to US coastal conditions and the enormous size of MOB.

Much depends on hydrodynamic and structural analysis towards the proper establishment of design loads, but by introducing both post-tensioned construction and high strength/high performance concrete as the material for the MOB sub-structure, both fatigue and durability issues have been documented as non-critical. Maintenance costs over 40 years of service life are considered low. This appraisal is based on more than 25 years of experience with in-service inspection of both fixed and floating concrete offshore structures. According to an independent study performed by Band, Lavis & Associates for the MOB S&T Program, the overall/replacement cycle for a concrete hull is 40 years compared to a 25 years for a steel hull. Further, it was stated that the overall maintenance cost for a concrete hull was 1/10th that for a steel hull. According to Aker, expected operating life for concrete platforms in the North Sea have been extended beyond 40 years without expectation for significant concrete maintenance or repair work. Inspection and repair techniques developed over many years of experience have been adapted and costed out for MOB.

The independent study by Band, Lavis & Associates also concluded that the acquisition cost for a complete MOB would about the same for either a steel or concrete hull material, however, it added that the life cycle cost for the concrete MOB would be about 17% less. Aker has established the construction cost estimate and schedule with a reasonable degree of accuracy. The basis for the estimate is the cost

database from Aker Maritime's previous concrete projects. The cost estimate for the concrete hull is also based on traditional dock construction. There is a potential for cost savings in adapting the "assembly line" approach, but this potential has not been pursued.

This task is complementary to the task discussed in Appendix B, Section 3.1.11 of transferring Navy marine concrete technology standards into the *Guide.*

3.1.6.2 Products

1. Aker Maritime, see following Table, Documentation for Phase 2 Study on Reinforced Concrete Materials for MOB Hull:

Aker Report Title	Report Number
Summary Report, Phase 2	58248-A0
Overall Description of the Detailed Design Process	58248-A1
General Fatigue Properties of Concrete Structures and Parameter Discussion	58248-A2-1
Computerized Fatigue Check Procedure	58248-A2-2
Fatigue Life Prediction for Concrete Semi	58248-A2-3
Concrete Used in Protective Structures, A General Report	58248-A3-1
Concrete Resistance to Impact and Explosion Loading	58248-A3-2
In-Place Behavior of Offshore Structures	58248-A4
Concrete Semi -Sensitivity to Overall Length	58248-A5
Concrete Mix Design	58248-B1
Durability of Offshore Concrete Structures	58248-B2-1
Creep, Shrinkage and Ice Abrasion	58248-B2-2
Coating and Membranes	58248-B2-3
Fire Resistance of Concrete	58248-B3
Project Execution Model	58248-C1
Construction Techniques	58248-C2
Concrete Repair Methods	58248-C3
Life Cycle Costs and Capital Cost Evaluation	58248-D1

2. Bjerkeli, L., J. Munkeby, and F. Rosendahl, High Performance Concrete - An Ideal Material for Large Floating Structures, Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds, R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 316-320, 1999.

3. Rognass, G., J. Xu, S. Lindseth, and F. Rosendahl, Mobile Offshore Base Concepts - Hybrid: Concrete Hull and Steel Topsides, Proceedings of the Third International Workshop on Very Large Floating Structures (VLFS '99), Vol. I, Eds, R.C. Ertekin and J.W. Kim, 22-24 September 1999, Honolulu, pp. 60-69, 1999.

4. Rosendahl, F., L. Bjerkeli, R. Borrensen, and J. Munkeby, Assessment of Present MOB Technology, ONR Contract No. BAA 98019, Report No. 58248-E1, Aker Engineering AS, Tjuvholmen, Oslo, Norway, 16 September 1999.

3.1.6.3 Resource

Aker Maritime, Aker Engineering AS, Tjuvholmen, Oslo, Norway.

3.1.7 FPSO Technology Review (WBS 2.1.7)

3.1.7.1 Advancements

The objective of this task was to document the breadth of connector use for floating production, storage, and offloading (FPSO) systems. These systems have large-scale steel connectors (yokes) joining riser-buoys with large storage vessels (converted ship hulls). They are required to remain on station in open ocean conditions. They are numerous and have been installed throughout the world, some of them for continuous exposure periods of 20 or more years. Though MOB connectors are likely to be subjected to order magnitude larger forces than FPSO connectors, the operating experience of FPSO's is germane to the design of MOB connectors due to their large size and longtime exposure requirements.

The results of this study would be integrated with other product areas concerned with the development of MOB connector technology, a major technical challenge in the S&T Program. For example, procedures involving the emergency-disconnect of modules prior to major storms is heavily discounted in FPSO operational experience. Instead, the experience shows that evacuation of personnel a more realistic emergency measure, for it is too difficult and disruptive of operations to disconnect and re-connect afterwards. Thus, all connectors for MOB, which require disconnect operations, could greatly benefit from a thorough review and understanding of this FPSO experience.

3.1.7.2 Products

1. Furgeson, K. and A. Patterson, Bearing Study for MOB Connector Application, Department of Mechanical Engineering, California Polytechnic State University, San Luis Obispo, CA, 4 June 1999.
2. MCA Engineers, FPSO Technology Review (Final Report), Contract N47408-97-D-0413, Oxnard, CA 93033, 29 May 1999.

3.1.7.3 Resource

California Polytechnic State University, San Luis Obispo, CA.

3.1.8 Initial Validation of MOB Classification Guide (WBS 2.1.8)

3.1.8.1 Advancements

The ABS with guidance from the Standards and Criteria Working Group had the responsibility for developing the MOB Classification Guide. Further, this had to be accomplished in an accelerated time frame. The issue addressed in this task was whether the content was consistent, and whether they made sense and were acceptable to the offshore structural design community. This was made more an issue due to the novelty of reliability-design features (and other aspects) in the approach to the Guide.

In this task, feedback of the end-user, i.e., the offshore structural design community, was sought on a running basis as the Guide evolved. During its second year of evolution, each of its intermediate revisions was subjected to an independent review in a design office setting. The assumption of the reviewers was that the Guide was to be used in a mock preliminary design. It was their job to document their opinions and its deficiencies while trying to make it work in this setting.

3.1.8.2 Products

1. MCA Engineers; periodic letter reports were prepared that advised on major deficiencies in intermediate revisions of the *Guide* as it evolved into the final product. This information reflected the view of the end user offshore structural design community.

3.1.8.3 Resource

MCA Engineers, Inc., Costa Mesa, CA.

3.1.9 Initial MOB Survivability Analysis (WBS 2.1.9)

3.1.9.1 Advancements

This study was directed towards survivability to hostile action. As a first step a previous survivability study for a smaller MOB concept was reviewed. One immediate conclusion was that a MOB's size was in its favor. The MOB S&T Program was not mandated to conduct a survivability analysis for a MOB. Nonetheless, it became clear to the Standards and Criteria Working Group that a MOB could not avoid harms way during its life span.

A formal survivability analysis is required for any new DoD platform in the ocean. However, such analyses presume that the specifics of the platform design are available, which is not the case for MOB. In spite of this, an initial survivability analysis was considered important. Specifically, this task conducted a weapons effects analysis and a threat assessment analysis for a MOB. A sanitized version of former was included in the *Guide*, in the form of a general discussion of weapons effects. The results of this initial survivability study are reported in two classified reports, and are not generally available. However, they somewhat corroborate the previous survivability study. For example, a MOB's large width, for example, provides magazine siting opportunities that mitigate certain threats.

Simultaneously, the Marine Corps published its Draft MNS for Maritime Pre-positioning Force for the 21st Century (MPF/F). It specifies Level I survivability, which is the lowest level requirement for Navy ships. If this is any indication of the requirement that will be imposed on a MOB, the survivability issue for MOB is substantially mitigated. Of course much depends on a MOB's prescribed mission, and on its specific design configuration.

3.1.9.2 Products

1. Wilson, D.T., Guidelines for Predicting Weapon effects Against the MOB, Naval Surface Warfare Center, Carderock Division, Survivability, Structures, and Materials Directorate, NSWCCD-TR-1999/20, In Process, CONFIDENTIAL, 1999.
2. Wilson, D.T., Section C.3.8 Weapons Effects in Preliminary MOB Classification Guide, Technical Report: AA99018, ABS Americas, Houston, December 1999.
3. Wilson, D.T., Threat Assessment for the MOB (U), Naval Surface Warfare Center, Carderock Division, Survivability, Structures, and Materials Directorate, NSWCCD-TR-1999/21, In Process, SECRET, 1999.

3.1.9.3 Resource

Naval Surface Warfare Center, Carderock Division.

3.1.10 MOB Explosive Safety Analysis (WBS 2.1.10)

3.1.10.1 Advancements

Most mission concepts for MOB include a requirement to store substantial amounts of ordnance aboard. For the purpose of design, the viewpoint taken of explosive safety for MOB was more that of a shore-side rather than a shipboard magazine. MOB's tremendous size permits this viewpoint, an indeed becomes an asset with regard to design for explosive safety. The objective of this task was to exploit this advantage, and provide a description of the design methodology for storage of ordnance aboard MOB. This description is included in the Guide. It conforms to the norms of the Department of Defense Explosive Safety Board (DDESB), as well as to the prescriptions of NAVSEA OP4 and OP5.

Specific analyses are not possible in the absence of prescribed quantities and types of ordnance materials to be stored. Some data on anticipated explosive weights could be and was inferred form a previous survivability study. Based on these data, and known mixes of ordnance materials stored aboard current ammunition ships, the net explosive weight and types of ordnance to be stored was inferred for purposes of analysis. These and other assumptions meant that the conclusions were best viewed as representative rather than specific. Nonetheless, the findings were imparted in the Guide, and tell a MOB designer that there are important DDESB standard procedures which must be followed, how to apply them by example, and where to find related explosive safety standards information.

Shore facilities normally achieve personnel safety, asset protection, and nonpropagation between potential explosive sources by separation distance (explosive safety quantity distance or ESQD data) requirements. Space and distance limitations on a MOB will generally not allow ESQD requirements to be met. However, a combination of separation distance (between adjacent MOB modules) and other mitigation measures (nonpropagating walls, venting, water spray, etc.) can work to prevent sympathetic detonation between adjacent modules. Therefore, while it is possible to lose one module, it is not likely that an entire MOB would be lost due to sympathetic detonation in the event of an accidental explosion.

3.1.10.2 Products

1. Tancreto, J.E., Section C.10 Accidental Explosions in *Preliminary MOB Classification Guide*, Technical Report: AA99018, ABS Americas, Houston, December 1999.

3.1.10.3 Resource

Naval Facilities Engineering Service Center, Port Hueneme, CA.

3.1.11 Marine Concrete Specification for MOB (WBS 2.1.11)

3.1.11.1 Advancements

The ABS was not required to provide a specification for marine concrete materials in the Guide, and neither is it disposed to do so. Yet MOB clearly involves concrete materials as it is conceptually configured. Even if reinforced concrete is not used for the hull material itself, the non propagating walls in the explosive safety system would probably best be constructed of concrete for maximum effectiveness. There is also a possibility that the top deck runway could be reinforced concrete. Further, the Navy has developed special concrete standards for marine applications beyond those used commercially by industry.

The intent of this task was to assemble, review and transfer Navy marine concrete technology standards to the ABS for inclusion in the *Guide*. Thus it is complementary to Aker's more extensive assessment of marine concrete for MOB discussed in Appendix B, Section 3.1.6. The specification developed in both tasks was considered for intermediate versions of the *Guide*. However, the *Guide* proper did not support the appended information, and it was judged to have not fit well in the final version. For example, there were no requisite provisions for structural concrete design in the reliability-based framework of the *Guide*. Because of that incompleteness the marine concrete specifications from this and Aker's studies were never added to the *Guide*. It is recommended that this technology be refined and incorporated in future versions. Therefore the present *Guide* addresses steel construction exclusively.

Preliminary meetings were held with Det Norske Veritas (DNV) and ABS on this deficiency. DNV is a regulatory agency that oversees marine platforms in the North Sea, and they have extensive expertise in the use of concrete in the ocean. Agreement was reached in principle whereby the former would contribute required sections in any future government-sponsored augmentation of the *Guide*, as published by ABS. The augmentation would include the Navy specification for marine concrete.

An independently reviewed Navy specification for marine concrete is the main advancement from this work. Two international experts in marine concrete and offshore construction reviewed the specification through the auspices of ASCE.

3.1.11.2 Products

1. Burke, D.F., Durable Marine Concrete for the U.S. Navy," Naval Facilities Engineering Service Center, 1100 23rd Avenue, Port Hueneme, CA, 1998.

3.1.11.3 Resource

Naval Facilities Engineering Service Center, Port Hueneme, CA.

3.1.12 Environmental Compliance (WBS 2.1.12)

3.1.12.1 Advancements

From the start of the S&T Program there was a keen awareness of the burden of environmental compliance for a MOB. Moreover, there was concern for the potential ramifications of noncompliance during both shore-side construction and operation at sea of a very large floating structure. Shore-side environmental impact will depend on the MOB concept configuration and on the method of construction. There are also considerations for its impact on structural design of environmental regulations governing operation at sea. Most important is the potential for construction delays and higher costs if these considerations are not brought to the attention of the designer at the beginning of a MOB design project. Therefore, the *Guide* needed to address environmental compliance.

The Navy has its own interpretation of the vast body of regulations from the EPA and international regulatory agencies regarding naval facilities ashore and at sea. It was important, therefore, that Navy experts assemble considerations for environmental compliance design standards for MOB. A major issue is this regard is whether a MOB is considered a ship or a facility. The potential environmental problems attending a MOB acquisition program have been considered by such experts and the results appear in a direct contribution to the *Guide*.

Preliminary considerations for environmental compliance of a MOB have been documented.

3.1.12.2 Products

1. ABS Americas, Section C.12 Environmental Considerations in *Preliminary MOB Classification Guide*, Technical Report: AA99018, Houston, December 1999.

3.1.12.3 Resource

Naval Facilities Engineering Service Center, Port Hueneme, CA.

3.2 Criteria Subcategory (WBS 2.2)

3.2.1 Environmental Specification (WBS 2.2.1)

3.2.1.1 Advancement

This objective of this task was to deliver a complete, consistent, and realistic "metocean" specification of winds, waves, and currents suitable for subsequent development into a MOB design basis; converting the specification into a design basis is addressed in the *MOB Classification Guide*. Much of the work in this task was pioneering due to the need to specify metocean conditions at the unprecedented one mile MOB scale. *Deliverables from this subject task are critically important since uncertainties in the environmental loadings are considered to be far larger than the uncertainties in the hydrodynamic and structural models*. Two main deliverables were produced:

1) a comprehensive report that summarizes the present understanding of winds, waves, and currents up to a one mile spatial scale suitable for engineering design, and
2) two representative hindcast databases of vector descriptions of wind, waves, and currents: one for long-term, and one for short-term within extratropical storms.

Developing this specification was a formidable task, and not surprisingly, some information is still not available – for example, wave crest lengths at the unprecedented one-mile scale of the longest MOB platform.

The comprehensive report summarizes all existing theoretical and measured information regarding phenomena such as wind gusting, wave [spatial] spreading, joint distributions of parameters such as significant wave period and height, and internal wave and soliton models. The fact that a MOB would operate in many parts of the world over its lifetime made it appropriate to investigate generic *event-based* rather than *regional statistics-based* phenomenological descriptions. Fatigue (most probable), operational (associated with the suspension of air operations at a maximum 40 knot wind or cargo transfer at sea state 3), and survival (during typhoons and hurricanes) metocean conditions are addressed.

It is not prudent to assume that all future MOB platform architectures could reliably disconnect in order to allow the individual modules to maneuver away from incident storm paths like most ships do. So for completeness this specification includes extreme storms. This is particularly relevant for cases where hostile damage made disconnection impossible or alternatively disabled the propulsion system of a single module. Unfortunately, even after decades of study by government, academia, and the offshore industry there are only limited [joint] relationships considered universally applicable to extreme extratropical events. Consequently, the state-of-practice is to subjectively/randomly pick a "reasonable" number of historically measured storm parameter sets, analyze system responses to each one, and select the maximum response as representative of the true maximum value. However, this approach is so numerically intensive for a platform as large as MOB that only a small number of simulations are typically completed. This introduces an inherent danger in that if this set is statistically-unreliable due to its small size, it would translate to large errors in the MOB design. There is no simple remedy for this. For example, it is not an option to simply choose a strategy to conservatively overestimate survival wind and current velocities and wave heights and crest lengths, because that would quickly and unnecessarily drive

the acquisition price of a MOB platform beyond affordability. In fact, the few publications on this topic to-date have tentatively concluded that the joint probabilities of the important environmental parameters within extreme events appear to be too variable to reliably collapse into simple and universal "representative" analytical relationships for a design basis. Confidently resolving this question was beyond the scope of this short S&T Program. In the meantime, this S&T program placed a high priority on insuring that the environmental specification was as accurate as possible.

The second set of deliverables for this environmental specification package consists of two databases. The first is an interactive database of joint wind/wave/current hindcast descriptors at 23 sites, averaged over 6 hour/15 mile intervals, for 20 years. The current is the vector sum of any large-scale current (e.g., Gulf Stream) plus a local current driven by regional winds. This "global" database allows for extensive examinations of long term conditional and marginal environmental statistics for any site conditions of interest (e.g., distribution of wave heights associated with a 40-knot wind). A very capable graphical user interface is also provided which greatly eases the inspection of this data. This information will be directly useful for fatigue and operational analyses. The second deliverable includes hindcast data for 25 large Northwest Pacific typhoons simulated over a much finer 1 hour/1 mile [moving] grid. This information is immediately useful for "conditional simulations" of extreme events whereby multiple analyses are [brute force] conducted using representative individual storms from this finite population. As stated above, this is a very time consuming and therefore nonoptimum analysis approach that will hopefully be improved upon in future metocean studies beyond this Program.

3.2.1.2 Products

1. Bechtel National, Inc., Environmental Specification for the Mobile Offshore Base, March 1999.
2. Bechtel National, Inc., Program MOBENV to query and display data from the databases (MATLAB code; user manual included in 3.2.1.2.a).
3. OceanWeather, Inc., Global hindcast database of wind, waves, and currents at 23 sites, 1999.
4. OceanWeather, Inc., Typhoon hindcast database (one main file, with complementary local current file).
5. Pawsey, S. and M. Manetis, Environmental Specification for the Mobile Offshore Base (MOB), Proc. 3rd Int. Workshop on Very Large Floating Structures, VLFS '99, Honolulu, HI, September 22-24, (ed. R.C. Ertekin and J.W. Kim), pp.172-180, 1999.

3.2.1.3 Resource

Bechtel National, Inc. was the prime resource for this task. They were supported by a large number of oceanographic experts with their relevant expertise:

Name	Expertise
Dr. Leon Borgman	Wave Statistics
Dr. Allin Cornell	Probability Theory
Dr. Mark Donelan	Waves
Dr. Rob Pinkel	Internal Waves

Dr. Emil Simiu	Wind
Dr. Bob Weller	Local, wind-driven currents
Dr. Jun Zhang	Extreme Waves
Naval Research Laboratory	Global currents

3.2.2 Spatial Coherence of Ocean Waves from Surface Scanning Radar Altimeter Data (WBS 2.2.2)

3.2.2.1 Advancements

This task had two parts. The first subtask was to collect Scanning Radar Altimeter (SRA) wave data from storms of opportunity. A NASA aircraft carries the (developmental) SRA scanner, which then produces a "2D+1" (two horizontal dimensions plus time) mapping of the instantaneous ocean surface elevation field under the aircraft. Data sets were successfully collected off Tasmania and two hurricanes. The most valuable data set for MOB consists of measurements of seven of eight octant wavefields in Hurricane Bonnie – which is significant because it is the first time such a complete wavefield had been measured in a tropical storm. Bonnie was a large category 3 hurricane with recorded wave heights up to 19 m.

One intriguing partial wave field from Bonnie is shown below in Figure B-1. The SRA-derived waves north of the eye of Hurricane Bonnie are shown with respect to North pointing to the top of the figure. The degree of positive displacement (crest) is indicated in white while black corresponds to negative displacements (trough). This panel size is roughly 1 kilometer wide by 6 kilometers high. The arrows illustrate an extreme wave with a 60 foot height and a coherent crest length over 1 kilometer wide.

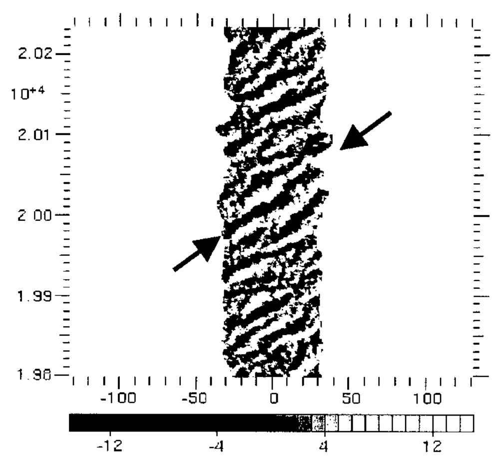

Figure B-1. SRA-derived waves north of the eye of Hurricane Bonnie.

The second half of this study was to develop algorithms for inspection of the data, with subsequent analysis to look for statistical patterns. The goal is to produce a "storm atlas" of useful wave parameters for extreme events. That work is still underway. A key question is "how adequately does linear, directional, statistical wave theory approximate the spatial structure and patterns of storm wave systems?" (If true, then existing software can be confidently applied to MOB design.) Preliminary results show that the SRA scanner and processing will be a useful tool for gathering wave data. Trial algorithms have been developed and demonstrated to locate and display the geometries of crests and trough lines, although the precise spatial definition of "a wave" is still unclear (to all participants). The degree of grouping

observed in the waves seems to differ from linear wave theory, although not to a level that would preclude use of that theory for design purposes. Four types of presentation formats are under development and evaluation: (1) "shiftplots", (2) spatial maps of local extrema, (3) closed-contour statistics maps, and (4) spatial directional covariance and coherence graphs.

3.2.2.2 Products

1. Borgman, L., et al., Storm Wave Topography: Creating a Design Engineer's Atlas of Realistic Sea Surface Features from SRA Measurements", Proc. 3rd Int. Workshop on Very Large Floating Structures, VLFS '99, Honolulu, HI, September 22-24, (ed. R.C. Ertekin and J.W. Kim), pp.181-189, 1999.
2. Walsh, E. J., C.W. Wright, D. Vandemark, W.B. Krabill, A.W. Garcia, S.H. Houston, M.D. Powell, P.G. Black, and F.D. Marks, Hurricane Directional Wave Spectrum Spatial Variation at Landfall, J. Phys. Oceanography, in preparation.
3. Wright, C.W., E.J. Walsh, D. Vandemark, W.B. Krabill, A.W. Garcia, S.H. Houston, M.D. Powell, P.G. Black, and F.D. Marks, Hurricane Directional Wave Spectrum Spatial Variation in the Open Ocean, J. Phys. Oceanography, submitted for publication.

3.2.2.3 Resource

Leon Borgman, Inc., and faculty at the University of Wyoming, with an associated contract for SRA data to Ed Walsh of NASA.

3.2.3 Synthetic Aperture Radar (SAR) Measurements of Wave Coherence (WBS 2.2.3)

3.2.3.1 Advancement

This project investigated spatial properties associated with ocean wave fields using Synthetic Aperture Radar (SAR) data. Development and evaluation of analysis algorithms were a key task as well. SARs aboard the Space Shuttle can measure instantaneous wave elevations with a 25m-grid spacing over a 100km-by–100km extent; similar systems aboard satellites can achieve comparable or better resolution (see WBS 1324). The ultimate payoff from both SAR studies (this one and WBS 1324) would be that it makes available the extensive ocean coverage of SAR wave data available for different areas and conditions. This would provide the Navy and the MOB project with a huge database of real observations of spatial coherence to help in design and evaluation of MOB and other systems.

Data analysis has been especially fruitful in examining imagery in the vicinity of Hurricanes Josephine and Bonnie. Limited conclusions from this data show that wave crests are much longer in the ocean than would be expected from linear theory. Figure B-2 shows the number of wave crests per square kilometer longer than the abscissa that were found in Hurricane Bonnie SAR imagery. The upper, thicker curve is from the data while the lower, thinner curves are from linear simulations. For example, one could infer from the data that two wave crests longer 1500m would occur in a 10 km^2 area. Linear theory predicts no such wave crest lengths would be encountered.

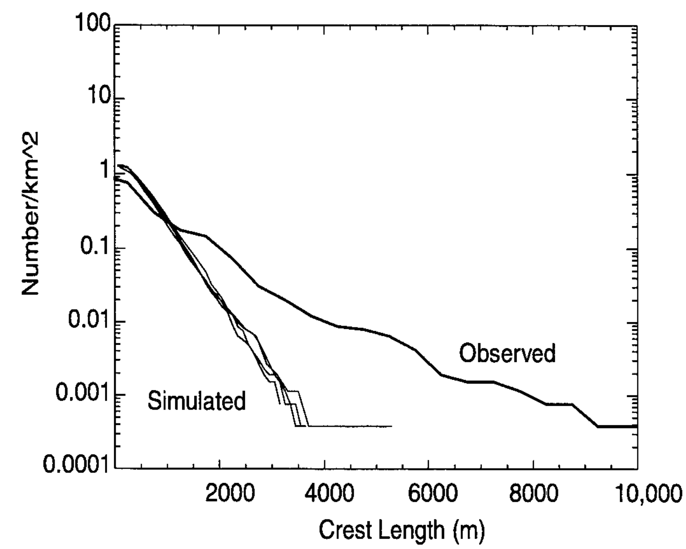

Figure B-2. The number of crests having a length greater than the abscissa for Hurricane Bonnie.

Groupiness, which is the tendency for large waves to group together in packets, is another important wave field descriptor for any ocean structure like MOB. This can be statistically estimated using the envelope of the spatial autocorrelation of the wave field. For these storms, a distinct groupiness pattern was detected with a spatial period of 2.5km. In other words, one would expect especially large groups of

waves separated by 2.5km – here, about ten wave periods. Artificial wave fields simulations using linear theory did not exhibit this groupiness behavior. This is additional (albeit preliminary) evidence that linear wave theory may not be adequate for large-scale studies of ocean waves.

3.2.3.2 Products

1. Alpers, W. , D. Ross, and C. Rufenach, On the detectability of ocean surface waves by real and synthetic aperture radar, J. Geophys. Res., 95:6481–6498, 1981.
2. Elachi, C. and W. Brown Jr., Models of radar imaging of ocean surface waves, IEEE Trans. Antennas Propag., AP-25:84–95, 1977.
3. Hasselmann, K., R. Raney, W. Plant, W. Alpers, W. Shuchman, D. Lyzenga, C. Rufenach, and M. Tucker, Theory of synthetic aperture radar ocean imaging: A MARSEN view, J. Geophys. Res., 90:4659–4686, 1985.
4. Monaldo , F. and D. Lyzenga, On the estimation of wave slope- and height-variance spectra from SAR imagery, IEEE Geosci. Remote Sensing, GE-24: 543–551, 1986.
5. Monaldo, F.M., Measurement of wave coherence properties using spaceborne synthetic aperture radar, JHU/APL Tech. Rep. SRO–00–01, 19 pages, January 2000.
6. Monaldo, F.M., Measurement of Wave Coherence Properties Using Spaceborne Synthetic Aperture Radar, Marine Structures Journal, in press, 2000.

3.2.3.3 Resource

Dr. Frank Monaldo, Johns Hopkins University Applied Physics Laboratory.

3.2.4 Wave Coherence Measurements Using Synthetic Aperture Radar (WBS 2.2.4)

3.2.4.1 Advancement

This second funded study of SAR data sets uses satellite measurements that have a spatial resolution of 12.5m. There are two basic objectives to this program: (1) to develop the appropriate measures of wave coherence and methods of application for SAR image data, and (2) to apply the methods to available SAR data sets. This investigation focused on locations in the ocean with high waves where two SAR paths cross in close time proximity in order to reduce problems related to azimuthal distortion in the raw data. The sea state patterns were analyzed and cross-compared to improve the statistical reliability of the data. This study is complimentary to the other SAR proposal (see WBS 1323).

Two issues with all SAR data sets is that (1) they do not see waves propagating in a direction orthogonal to the orbital motion, and (2) accuracy decreases with increasing wave height. This study is filtering wavefields to get 2-dimensional filtered (smoothed) wave number spectra $S(k_x,k_y)$, then using them to generate families of numerically-constructed wavefields. The resulting elevations are then hard-clipped at plus/minus one sigma to isolate crest and trough patterns. Results show that crest lengths following a cumulative exponential distribution given by $N(\lambda)/N_o=\exp(-\lambda/\lambda_o)$ where λ_o = only required parameter. The conversion process for the raw SAR data appears to produce artificially longer crest lengths (which can be corrected), but with an unbiased estimate of the mean incident direction (except for quadrant ambiguity). Preliminary inspection of an Oregon (Pacific) data set showed 6km coherent crest lengths for swell. A second study looked at data off Labrador where SAR, altimeter, and TOPEX data sets overlapped. The approach chosen for this filtering was to truncate the 2D spectral ordinates if they were less than ten percent of the peak. Preliminary inspection of this (Atlantic) data indicates up to 2km crest lengths. In closing, it is felt at this time that estimated crest lengths (and angular spectral widths) may be 20-30% too long for 500m wavelengths, and 20% to 40% at 200m wavelengths depending on H_s and the SAR look direction. A third data set was analyzed near Duck, NC to use results from the in-situ wave array located there as a reference. The directional width of this SAR-image spectrum (after processing) is only about 30% larger than the FRF spectrum (as projected to the depth of the ERS measurement). This indicates the utility of the SAR inversion algorithm in improving wave coherence estimates from SAR image data.

3.2.4.2 Products

1. Walker, D.T., D.R. Lyzenga, and M.A. Renouf, Characterizing wave coherence with satellite-based synthetic aperture radar", Proc. 3rd Int. Workshop on Very Large Floating Structures, VLFS '99, Honolulu, HI, September 22-24, ed. R.C. Ertekin and J.W. Kim, Vol. I, 29-36, 1999.

2. Walker, D.T., D.R. Lyzenga, and M.A. Renouf, Characterizing wave coherence with satellite-based synthetic aperture radar, Marine Structures Journal, in publication, 2000.

3.2.4.3 Resource

Dr. David Walker and Dr. David Lyzenga, ERIM International, Inc.

3.2.5 Observations and Modeling of Spatial Wave Coherence (WBS 2.2.5)

3.2.5.1 Advancement

This study is investigating wave spatial coherence using data collected by one of the co-PIs using both a compact 6-element, and an extended 14-element array of capacitance wavestaffs deployed from a tower in a large lake. The fetch at this site varies from 1 to roughly 300 km, thus providing a wide range of wave development. The analysis made use of the "Wavelet Decomposition Method" (WDM) that permits the identification of individual waves of a given scale (here, frequency) and direction passing through the array at any time.

This data set is of particular value because the sea surface is measured directly and includes data accurately sampled at multiple fixed positions over hours of observation. While admittedly for a lake and not the open ocean, this data will nonetheless be useful for evaluating models of wave coherence and for comparison to data from other sources. "Crest lengths" (*i.e.* the along-crest correlation of high waves) were studied in two ways. In the first, both the WDM and conventional Fourier transform techniques were used to estimate the temporally averaged lateral correlation of the waves. The two methods agreed well (as they should), thus providing a check on the algorithms. In the second approach the lateral crest profile was *a priori* assumed to be approximately Gaussian. The WDM was used to determine the instantaneous approach direction of packets of waves. Triplets of wave staffs across the propagation direction were then used to estimate a characteristic crest length parameter for each wave crest. Remarkably, the relationship between crest length and the mean wavenumber was closely linear.; i.e., the average width of the crests to the half amplitude point was always about half the wavelength. Other analyzed cases showed a similar linear dependence between crest length and wavenumber, but the slope of the line depended on such external parameters as the wave age.

Lastly, the basic WDM model was extended to account for more than one unidirectional wave train at each wavelet scale and time. Preliminary verifications were encouraging and will continue.

3.2.5.2 Products

1. Donelan, M.A., W.M. Drennan, and E.A. Terray, Wavenumber spectra of wind waves in the range of 1m to 50m", in The Wind--Driven Air-Sea Interface: Electromagnetic and Acoustic Sensing, Wave Dynamics and Turbulent Fluxes, M. Banner (ed.), School of Mathematics, The University of New South Wales, Sydney, Australia, pp. 35-42, 2000.
2. Donelan, M.A., Wave propagation and wind-wave interaction", Abstract and presentation at the NCAR Geophysical Turbulence Program Workshop: Turbulence and the Air-Sea Interface. Boulder, Colorado, August 15-17, 2000.

3.2.5.3 Resource

Dr. Gene Terray, Woods Hole Oceanographic Institute, and Dr. Mark Donelan, University of Miami.

3.2.6 Spatial Coherence and Crest-length Statistics of Waves In Deep Water (WBS 2.2.6)

3.2.6.1 Advancement

The long-term objective is to determine how nonlinear (to second order) interactions and directional spreading affects the spatial coherence and crest-length statistics of ocean surface gravity waves. First, a synthetic three-dimensional wave field was simulated using an idealized frequency-direction spectrum (based on an assumed directional spreading) with second-order nonlinearities accounted for via a theoretically based bispectrum. As expected, simulations with narrow and broad frequency-directional spectra showed that groups are larger (more big waves in a row) and the crests are longer for narrow band sea surfaces than for the broad band waves (Figure B-3).

In the example sea surface shown in Figure B-3, wind generated waves with moderate directional spreading and second-order nonlinear waves are shown to be consistent with theory. The significant wave height is 5.7m and the colors of the sea-surface elevation are color coded: red signifies wave crests and dark blue signifies troughs. The small panels on the left and bottom of the color contours are 1D cuts through the center of the sea surface; the dotted lines on the sea surfaces show the locations of the 1D surfaces.

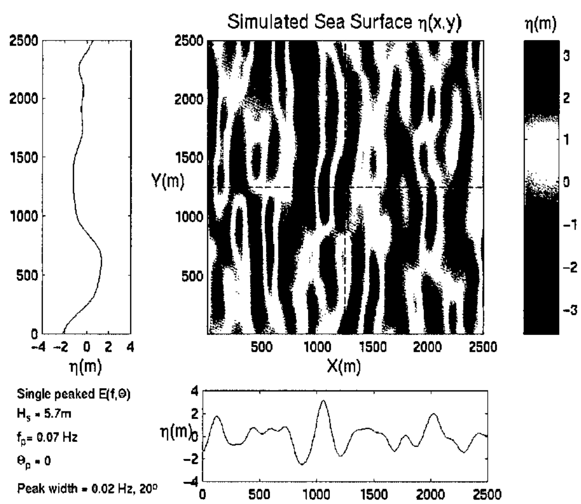

Figure B-3. Example sea surface consisting of wind generated waves with moderate directional spreading and second-order nonlinear waves consistent with theory.

Empirical wavenumber spectra were directly calculated for a wave field measured using a LIDAR system (data provided by P. Hwang, NRL of approximately 1 m high waves in 20-30 m water depth near the North Carolina coast). Two bispectra were then calculated: (1) directly from the wave data, and (2) indirectly by modifying the wavenumber spectra assuming the same second-order nonlinear theory used

above. These two bispectra and third-order statistics (skewness) compared well, implying that second-order theory was sufficient to model those waves. Lastly, the theory to determine the bispectrum from data collected from a moving platform (e.g., an airplane) has been developed.

3.2.6.2 Products

1. Herbers, T.H.C., Steve Elgar, N.A. Sarap, and R.T. Guza, Dispersion properties of surface gravity waves in shallow water, J. Physical Oceanography, submitted for publication, 2000

3.2.6.3 Resource

Dr. Steve Elgar, Washington State University and Dr. Tom Herbers, Naval Postgraduate School.

3.2.7 Nonlinear Dynamics of Three-Dimensional Wave and Wave-Group Interactions – Direct Computations (WBS 2.2.7)

3.2.7.1 Advancement

The goal of this study is to develop an accurate and robust physics-based model for synthesizing fully nonlinear three dimensional wave fields including wave-current and long-short wave interactions. The basis is a higher order spectral (HOS) model based on a generalized Zakharov approach. This model can be tailored to different design uses by trading off accuracy (the order of nonlinearity/wave steepness M) and computational burden (the number of component waves N). A dense set of Fourier Series harmonics is used for the [linear] basis vector set for the k_x and k_y component wavenumbers; the technique then iteratively determines the higher harmonics [up to order M].

Initial validations used laboratory measurements (courtesy of Professor M.H. Kim of the Texas A & M University) from a 46m x 30m wave-basin. The computed [bull's eye] wave elevations compared well with the measurements. A second set of validations was completed using Scanning Radar Altimeter (SRA)-based data from Hurricane Bonnie (courtesy of NASA/Ed Walsh). In that wavefield, swell and sea had comparable energy with a overall significant wave height of 9 meters. The HOS model used 3rd-order nonlinearity and 1024x1024 free-surface component waves, and results agreed qualitatively well to the measured data.

The uniqueness of the solution is still under study. While it has been shown that this approach can be made to successfully reproduce any finite number of *a priori* given/measured time histories distributed throughout a wavefield, the wavefield is also known to be nonunique for all positions between those probes depending on the initial conditions. A second issue is that the wavefield is inherently spatially periodic outside of the original bounds due to the integer relationships among the Fourier harmonics. The present computational effort is on the order of one day for typical choices of the field size, number of basis modes N, and order of nonlinearity M. HOS computations can also serve to corroborate experimental and field data, confirm analytical perturbation predictions, and provide initial- and boundary condition specifications for wave-basin investigations and/or fully nonlinear simulations of specific localized wave events.

3.2.7.2 Products

1. A manuscript addressing the developed iterative optimization scheme for reconstruction and forecasting of three-dimensional nonlinear wave-field evolutions has been completed and submitted to the *Journal of Fluid Mechanics*.
2. A second paper focusing on the comparisons of the HOS simulations to the wave-basin and field experimental measurements is in preparation for submission to the journal of *Applied Ocean Research*.

3.2.7.3 Resource

Dr. Dick Yue, Massachusetts Institute of Technology.

3.2.8 Spatial Coherence of Surface Waves by Nonlinear Green-Naghdi Model in Deep Water (WBS 2.2.8)

3.2.8.1 Advancement

The properties of the spatial coherence of the wave field (crest length, crest asymmetry) are being investigated using an Irrotational Green-Naghdi (IGN) model. The first step was to develop a nonlinear IGN model (to order M) to efficiently simulate fully nonlinear interactions in short-crested random wavefields. The accuracy and computational expense of the model is controlled by the 'Level' of the model, which is defined as the number of interpolation functions in the vertical direction. The two main tasks were (1) completion of an irrotational version of the IGN model and (2) development of visualization and analysis tools. The analysis included simulation of three dimensional synthetic sea surfaces with target directional spectra, quantification of the resulting spatial coherence (crest lengths), and then comparison to observations.

The first simulations studied rogue waves, which can be generated from a Stokes' wave train modulated by side-band (Class I) instability. One analytical study (see Appendix B, Section 3.2.9) predicted that the maximum wave height of rogue waves is 2.4 times the height of the carrier wave. This is based on the nonlinear Shroedinger (NLS) equation, which is derived under the assumption of weak nonlinearity. IGN simulations were performed using a Level III model and a range of initial wave steepness between 0.06 to 0.17. The computational domain was ten times the carrier wave length, and the Stokes wave was modulated with two sinusoidal waves with wavelengths 90% and 110% and amplitudes 5 % of the carrier wave. IGN numerical simulations showed that when the steepness of the Stokes' wave was small, the amplification due to the nonlinear modulation was about 2.4, which agreed well with Osborne's analytical result (and assumption of weak nonlinearity). However, the IGN model found a slightly higher maximum amplification of 3.1 for a steepness parameter of 0.1.

Multiple synthetic wave field studies were completed; one corresponds to Hurricane Grace (see, e.g., "The Perfect Storm" by Sebastian Junger). That storm was specifically selected to challenge the IGN model because a very extreme wave height of 100 ft was recorded. In the absence of accurate measurements the initial condition was assumed to be a unidirectional single-period swell and short crested random wind waves. The amplitude of the swell and the significant wave height of the wind waves were both 10 meters. The swell component was a modulated Stokes wave with an initial steepness $ka = 0.1$. Figure B-4 shows a time record of the synthesized nonlinear wave elevation at a fixed location. Also shown are the zero mean time history and two envelopes for waves produced from both linear and nonlinear IGN models; the envelope of the linear waves is shown as the relatively smooth blue dashed line at approximately ± 10 meters and the nonlinear IGN Level III envelope is shown as the oscillatory red dashed line that exceeds +20 meters. The maximum wave height reaches 34 meters around time = 1650 seconds, which is curiously more than the expected maximum value of 2.4 times the significant wave height discussed in the previous paragraph. The significance of this discrepancy is not yet clear, although it seems that the long swell plays a major role. Note that the multiplier is only 1.5 for the linear simulation.

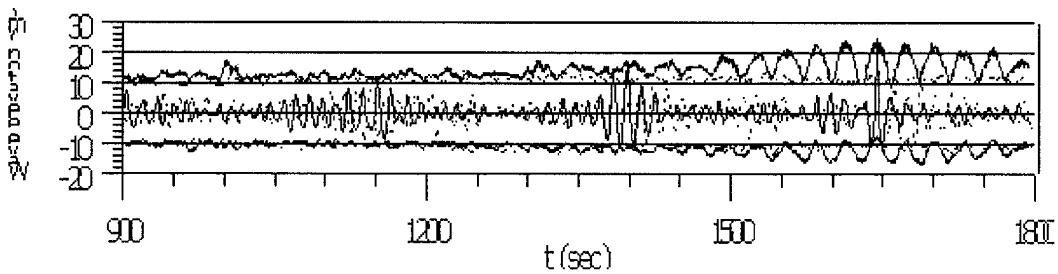

Figure B-4. Synthesized wave time history from the IGN model.

3.2.8.2 Products

1. Kim, J.W. and R.C. Ertekin, A Numerical Study of Nonlinear Wave Interaction in Irregular Seas: Irrotational Green-Naghdi Model, Proc. 3rd Int. Workshop on Very Large Floating Structures, VLFS '99, Honolulu, HI, September 22-24, ed. R.C. Ertekin and J.W. Kim, vol. I, pp.162-171, in press, Marine Structures Journal, 2000.
2. Kim, J.W. and R.C. Ertekin, Numerical Simulation of the Ocean Surface by the Irrotational Green-Naghdi Model, submitted to WAVES 2001, The 4th International Symposium on Ocean Wave Measurement and Analysis, September 3-5, 2001, San Francisco, CA, 2001.
3. Kim, J.W., K.J. Bai, R.C. Ertekin, and W.C. Webster, A Derivation of Green-Naghdi Equation for Irrotational Flows, in press, Journal of Engineering Mathematics, 2000.

3.2.8.3 Resource

Dr. Cenzig Ertekin and Dr. Jang Whan Kim, University of Hawaii.

3.2.9 Modeling of Rogue Waves using the Nonlinear Shroedinger Equation (WBS 2.2.9)

3.2.9.1 Advancement

This study is modeling nonlinear ocean waves using the nonlinear Shroedinger (NLS) equation. The emphasis is on the phenomenon of "rogue waves and holes" which are a nonlinear manifestation of extreme dynamical behavior in deep water. Studies are done both numerically and analytically via the Inverse Scattering Transform (IST), which defines rogue waves as a ratio of Riemann Theta Functions organized into three summation terms: (a) Gaussian and small other nonGaussian, (b) rogue components, and (c) nonlinear interactions. This decomposition on integer harmonic vectors has been labeled "Nonlinear Fourier Analysis"; note that the use of Fourier harmonics basis components constrains the IST solution to be periodic in space and time.

While rogue wave properties are not well understood, their physical and statistical properties are certainly governed by nonlinear effects such as the Benjamin-Fier (Type I) instability and the Type II instability. This study will address certain aspects of these two instabilities. Two sets of wave data were analyzed: (a) one from a wave tank in Florence, Italy, where measurements were obtained as part of this study, and (b) the other from a downward looking laser wave sensor mounted on a North Sea oil platform. An additional part of this study was a preliminary analysis of theoretical formulations for both unidirectional wave motion and for motion governed by directionally spread wave trains. A preliminary investigation of how to extend IST to the deep water domain will allow for a preliminary evaluation of inverse scattering theory and will provide an entirely new perspective for addressing the nonlinear dynamics of deep-water rogue waves and wave trains in general.

The North Sea fixed oil platform data has definitely identified rogue waves (isolated waves significantly larger than the surrounding waves). Initial numerical studies have shown that any initial wave profile, even monochromatic, will eventually develop nonlinear (rogue) components if it has even minor amplitude modulations in either the direction of propagation or transverse to it. For 1,000 wave cycles, one-dimensional IST simulations require about 1 hour of CPU time and 1GByte of memory. Experimental waves have been obtained in a 50m by 1m wave tank in Florence, with twelve wave probes for nonlinear spatial evolution validations. Another important discovery is that rogue waves are enhanced in 3D simulations compared to 2D simulations.

3.2.9.2 Products

1. Osborne, A., Rogue Waves and Holes in the Sea, Report 9-2-99, Department of Physics, University of Turin, September 1999.
2. Osborne, A., The Random and Deterministic Dynamics of "Rogue Waves" in Unidirectional, Deepwater Wave Trains, Proc. 3rd Int. Workshop on Very Large Floating Structures, VLFS '99, Honolulu, HI, September 22-24, (ed. R.C. Ertekin and J.W. Kim), vol. I, pp.14-22, 1999.

3.2.9.3 Resource

Dr. Al Osborne, University of Torino (Italy).

4 RECOMMENDATIONS

4.1 Metocean Issue: Characterization of Wave Crest Lengths

There are several distinct unresolved issues regarding environmental modeling for MOB design. Perhaps the most critical issue is the need to quantify wave crest lengths versus metocean conditions. Of course this is an issue only for waves that are broadside to the long MOB platform. In such cases studies have shown that module and connector stresses are particularly sensitive to the torquing response. So the first question is what metocean conditions should be included in a wave crest study? Even this is not easily answered. Would a MOB platform ever be operating while subjected to distant swell at that incident angle? Yes, that is likely, and such waves are long-crested. At the other extreme, would a MOB platform ever be subjected to hurricane waves at that near beam-on angle? Under normal conditions the answer is no, the modules would disconnect prior to the arrival of any storm. But what if two modules remain connected due to a damaged connector? The answer may still be no, assuming that the dynamic positioning system is operating normally, but is it not logical to conclude that the cause of the connector damage (e.g., a hostile explosion) may have also rendered the dynamic positioning system inoperative? Then yes, a short MOB platform could go broadside in hurricane/typhoon seas, and in that case designers would need to know if such storm waves were ever sufficiently long crested to excite the problematic torque responses. The preceding scenarios first must be addressed by ABS and the Guide Working Group and wave studies continued to satisfy all design scenarios. Similar questions regarding wave crest lengths apply for fatigue and operational calculations. The fact that the wave crest lengths (i.e., wave coherence) affect so many scenarios was recognized early in the MOB Program. Sections 3.2.2 to 3.2.9 of this Appendix reported research into wave coherence. Those studies are providing a "first look" at the problem but much work remains.

4.2 Metocean Issue: Characterization of Extreme Metocean Excitations

This issue is integral to the techniques described in the Modern methods for identifying maximum response topic contained in Appendix B, Section 3.1.1. That section addresses the urgent need to develop rational guidelines for minimizing the number of numerical studies required obtaining statistically valid extreme responses estimates. In fact no single technique has yet been selected for those studies. And as discussed in Appendix B, Section 3.1.1, the present state-of-practice for specifying wind/wave/current for large storms is essentially brute force and subjective. For typical marine structures increasing the number of numerical studies can compensate for the large design uncertainty associated with this approach. Unfortunately, the corresponding computational burden for a large MOB platform makes that approach suboptimal. The goal of these studies would be to continue the search for vector relationships among winds, waves, and currents versus radius in large storms. A final related topic recognizes that while the 20 years of hindcast database information per site is considered reasonably accurate for engineering purposes it may be only marginally sufficient for accurately extrapolating the joint statistics of extreme events of 100 or more year return periods, which may be required by the Guide.

4.3 Metocean Issue: Characterization of Metocean Phenomena

Further study is warranted to better define engineering models for internal waves, solitons, and storm fronts. As with wave coherence, large, deep draft MOB platforms are expected to be more susceptible to

such phenomena compared to conventional marine structures. As described in Appendix B, Section 3.2.1, the present *Preliminary MOB Classification Guide* does include approximate engineering models for these conditions but more accurate descriptions are necessary for all of them. Their importance with respect to MOB behavior is not fully understood at this point, particularly as they affect the capabilities of the dynamic positioning system.

4.4 Damage Stability

Stability work should be continued, especially for the unprecedented scenario of a damaged connector and damaged/flooded module connected to an intact module. The study should address thresholds for environmental excitations in such situations, and progressive failure and mitigation procedures.

4.5 Survivability and Weapons Effects

A systematic study is required of the vulnerability and survivability of MOB. However, much depends on MOB's mission. For example, the Draft MNS for Maritime Pre-positioning Force for the 21st Century (MPF/F) establishes minimal weapons effect requirements. Regardless, the integrity of semisubmersible hull forms to weapons effects has not been studied. Design features that minimize structural damage to steel and or concrete semisubmersible hull forms due to air blast, underwater shock, fire, flooding, explosion, etc. need to be developed consistent with MOB missions. Additionally, performing a survivability analysis of the MOB will require blending of analysis technology from the warship and land-side communities, since many of the functions performed by the MOB have no analog in aircraft carrier missions (the only comparable floating platform). The survivability analysis also needs to take into account the detailed concept of operations of the MOB, so that synergistic defensive capabilities can be considered. It would be better to get an early start on the survivability analysis so that any problems with the MOB itself, or in the methodology used to assess its survivability, can be identified and corrected before any final design would be undertaken.

4.6 Explosive Safety

Large amounts of ordnance will be stowed on the MOB that could lead to catastrophic damage to the platform if struck by threat weapons or subjected to an accident. Development of sympathetic detonation criteria for all of the weapons stored on the MOB will require additional testing and analysis. This is an important topic that complements item #3 above since the integrity of semisubmersible hull forms to weapons effects is unknown. The final design of an explosive safety system must be based on fundamentals, and should be validated with full-scale testing of a donor and an acceptor magazine. Design concepts must consider the special requirements of a MOB structure and be developed in conjunction with survivability design measures.

4.7 Setting of Target Reliabilities

The Guide currently contains target reliabilities, which all designs are required to satisfy. These reliabilities have been derived through a rigorous process of analytical predictions and comparison with other large engineered systems on the basis of the cost of failure as well as the risk to human life. Target reliabilities for individual MOB components and failure modes have been set on a uniform risk basis. However, only a very rudimentary attempt was made to take account of other factors such as strategic and

political value. This is a subject that requires careful consideration, and should only be undertaken with the participation of the owner of the system. The process involves making tradeoffs between several factors, many of which are difficult to quantify.

4.8 Development of Partial Safety Factors

Partial safety factors are applied to the load and the structural resistance variables in the design process, and are a measure of the safety in the structure. These factors depend on target reliabilities, the uncertainties in the relevant design variables, and the accuracy of the design and analysis procedures. As such the factors depend to some extent on the structural form and response characteristics of the platform under design. The Guide contains detailed guidance on how MOB partial safety factors may be derived and provides initial estimates for them. However, further work is essential to better quantify these estimates.

4.9 Uncertainty in Design and Analysis Tools

Some of the major sources of uncertainty in the MOB technology remain to be systematically quantified. For example, uncertainties in maximum connector stresses are the product of the uncertainties in: how representative the finite set of storm parameters are; the mathematical treatment of the incident waves; the inherent simplifications in the hydrodynamic model; the refinement of the hydrodynamic numerical discretization; how the hydrodynamic loads are passed to the structural model; and finally the refinement and element selection of the structural (finite element) discretization. The same set of uncertainties applies to fatigue stress studies. Efforts to logically identify and assess all of these uncertainties should be continued. In particular, the uncertainty in the accuracy of the analysis tools should be determined through validation of each of the available analytical or numerical tools using appropriate test results. Based on these uncertainties, the required load and resistance factors can be systematically evaluated for designing the structural components of the individual MOB modules.

4.10 System Reliability

Because of its unprecedented nature, methods for systematically assessing the reliability of various MOB systems have not been fully developed and critically evaluated. Examples include structural integrity, stability (intact and damage scenarios), and dynamic positioning. This requires information describing the reliability of all constituent elements, as well as the reliability of the complete and connected MOB platform and connectors. As the reliability of a system is a function of the reliabilities of its constituent components, the reliability of the system must be assessed on the basis of the reliabilities of the respective components. The method, therefore, should synthesize the reliabilities of the components that will lead to the reliability of a module. Then, with the reliability of each module, and the accompanying reliabilities of the connectors, assess the system reliability of the assembled MOB. Sample remedies would include component redesign and/or a change in functions.

4.11 Reliability-Based Maintenance

To maintain a prescribed target reliability (e.g., against excessive fatigue damage), the schedule for inspection and repair of critical joints in the modules must also be reliability based. Although this has been recognized, efforts to formulate and develop such reliability-based maintenance schedules have not

been undertaken. As demonstrated in the case of oil tankers, notwithstanding the difference between the MOB and oil tankers, it is difficult to insure high reliability for long fatigue lives unless accompanied by regular maintenance. Such a reliability-based maintenance strategy is essential also to insure the target reliability of the connectors over the life of the MOB. Indeed, because of the essential role of the connectors for maintaining the connected mode of the MOB system, the development of the necessary reliability-based maintenance schedule to maintain a minimum prescribed target reliability of the connectors against fatigue and fracture failure is clearly of critical importance.

4.12 Acceptance of Guide by Offshore Designers

The proposed reliability-based Guide represents a quantum jump from that which is reflected in presently available ABS rules. With limited manpower allocated to the Guide's development for only two years, it can be expected that it will not be as complete as present rules. The Guide is to be used by experienced offshore designers with a lot of detail to be supplied from experts; this is considered unavoidable given the fundamental nature of the Guide for treating the unprecedented design challenges ubiquitous to MOB. Testing of the Guide should be a continuous requirement. Past attempts at testing were done to discover major deficiencies and provide suggestions for improvements. This proved difficult because the Guide was under constant revision. When the Guide becomes somewhat more stabilized, a more organized hands-on evaluation should be resumed.

4.13 Fracture-Based Fatigue Analysis of Connectors

The new fracture mechanics-based long crack growth rate fatigue model described in Appendix B, Section 3.1.4 forms a promising beginning for the proper design of oversized components such as connectors expected in a MOB design. But that one advance does not provide the complete answer for fatigue. For example, more experimental research is needed to validate that new long crack model for both inert and aggressive environments. Basic and applied research is needed to develop a complementary model for short crack growth for thick steel plate. Further, corrosion-fatigue may be serious enough for MOB connectors to be replaced every five to ten years at a cost of $50M to $100M per connector. Additional applied research is needed to find quicker ways of mitigating corrosion-fatigue.

4.14 Codification of Modern Concrete Construction Materials

The use of high volume fly ash (HVFA) concrete mixtures is a technology issue with a high cost payoff that has not been sufficiently pursued regarding MOB hull construction. Development of HVFA technology could result in very significant benefits with regard to lower capitalization cost improved concrete durability, and the effective use of sustainable material technologies. The concrete construction industry has proven the feasibility of using HVFA concrete mixtures, but national construction standards have not been developed. Demonstration and validation of HVFA technology for MOB hull construction should be accomplished prior to the inclusion of marine concrete standards into the Guide.

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Design Tools

1 OVERVIEW

1.1 General Description

The large scale and complexity of proposed Mobile Offshore Base (MOB) designs are unprecedented in comparison to conventional ships and offshore platforms. The principal functional uniqueness for MOB relates to (1) modules transiting from one station to another with full payload in all metocean conditions, and (2) connecting and operating multiple-module platforms at sea. Substantial extensions of design tools from the state-of-the-engineering are required to analyze and optimize prospective designs, to ensure their safety, and to minimize their overall cost.

The objective of the Design Tools product area was to complement the *MOB Classification Guide* by providing a suite of validated computer software for all hydrodynamic and structural analyses of a MOB. At the inception of the MOB S&T Program, hydroelastic models for estimating the wave-induced motions and wave field for large, floating structures with structurally elastic responses such as a MOB were numerically inadequate and/or unvalidated. This was a fundamental deficiency that affected many design issues: acceptability of dynamic runway motions, connector loads, dynamic motion requirements for cargo handling from vessels and lighterage, air gap, guidelines for connecting and disconnecting modules, and dynamic positioning requirements. This deficiency established the need for this Product Area which has two parts. The objective of the *Hydrodynamic Models* subtask was to develop and enhance suitable numerical models, particularly hydroelastic models. The objective of the *Validation Data* subtask was to obtain experimental data to validate their applicability's and accuracy's.

The main thrusts of this Product Area were to:

- Develop and/or advance hydrodynamic and hydroelastic models.
- Conduct model tests to generate high quality data for model validations.
- Develop a load generator interface for mapping hydrodynamic pressures from the hydrodynamic panels onto the structural elements.

The motivation for the latter deliverable was to provide analysts with the most accurate possible modeling capability, by providing a direct link between the best hydrodynamic models and already-mature finite element structural models.

1.2 Quality Assurance

Quality assurance measures for this product area consisted of contract deliverable review, quarterly contract review meetings, semi-annual MOB Technology Exchange Conference, and two working groups on hydrodynamic model development and validation data. Draft contract deliverables were reviewed by

both outside consultants and in-house government experts. The official government comments were summarized and compiled from each individual comment and forwarded to contractors for inclusion into the final deliverables. On-site quarterly contract review meetings were held to monitor the progress of key products, provide opportunity for communication between the government and the contractors, and to resolve any outstanding administrative and technical issues during the last quarter of contractor performance.

All participants in this product area were required to present their technical status to the MOB project team at the Semi-annual MOB Technology Exchange Conferences. The presentation often resulted in valuable inputs from other Program participants. These conferences provided an excellent forum for exchanging and sharing technical ideas, particularly in the model development and enhancement tasks since some technical advances by one contractor can be applied to others in their works.

In addition, Design Tools Working Group meetings were held during the MOB Conference to provide opportunities for more in-depth and focused discussions specific to the design tools product area. The participants included invited consultants experts, key product area participants, and government representatives. Two specialized working groups were formed, namely, the Hydrodynamic Models Working Group and Hydroelastic Testing Working Group.

1.2.1 Hydrodynamic Models Working Group

The Hydrodynamic Models Working Group assessed the general focus of the MOB model developments and evaluated gaps and overlaps among the studies. Membership in this working group consisted of:

Name	Organization
Dr. Rueybin Chiou	Product Leader, Naval Facilities Engineering Service Center
Dr. Subrata Chakrabarti	Offshore Structural Analysis, Inc
Mr. Mike Edwards	McDermott Technology, Inc
Dr. Jeff Falzarano	University of New Orleans
Dr. Jim Garrison	C.J. Garrison & Associates
Dr. Tom Korsmeyer Dr. David Kring	Massachusetts Institute of Technology
Dr. Dave Kriebel	U.S. Naval Academy
Dr. John Letcher	AeroHydro, Inc.
Dr. Woei-Min Lin	Science Applications International Corp.
Mr. Makis Manetas	Bechtel National, Inc.
Dr. David Raj	McDermott Technology, Inc.
Dr. Ron Riggs	University of Hawaii
Mr. Tim Smith	Naval Surface Warfare Center – Carderock Division
Prof. Marshall Tulin	University of California at Santa Barbara

1.2.2 Hydroelastic Validation Data Working Group

This working group was specifically tasked with direct oversight of the MOB hydroelastic validation test at the Naval Surface Warfare Center Carderock Division (NSWCCD). The primary focus of this group was to evaluate as-built test preparations including model construction, wave properties, instrumentation, and data collection techniques. The membership in this working group consisted of:

Name	Organization
Dr. Rod Barr	Hydronautics Inc.
Dr. Subrata Chakrabarti	Offshore Structural Analysis Inc.
Dr. William Webster	Ship Research Inc.
Dr. Paul Palo	NFESC

Prior to the test, a MOB-sponsored 2-day workshop of internationally recognized hydrodynamics experts was held in May of 1998 to evaluate whether laboratory scale validation tests would contribute to the MOB model development. While not a formal working group, the following participants made presentations outlining the key issues and their views regarding proposed hydroelastic testing and data interpretation:

Name	Organization
Dr. Rod Barr	Hydronautics Inc.
Dr. Subrata Chakrabarti	Offshore Structural Analysis Inc.
Dr. Jim Garrison	C. J. Garrison Inc.
Dr. Fred Raichlen	California Institute of Technology
Prof. Marshall Tulin	University of California at Santa Barbara
Dr. William Webster	Ship Research Inc.

The presentations and conclusions from the group discussions are documented in:

> Mobile Offshore Base Hydroelastic Model Test Conference, 27-28 May 1998, MCA Engineers (ed.), Naval Facilities Engineering Service Center, Port Hueneme, CA.

There were two core questions: (1) would a small scale laboratory physical model, wave conditions, and instrumentation be sufficiently accurate and representative of full-scale hydroelastic behavior, and (2) was there enough uncertainty over the assumptions inherent in the analytical/numerical models to warrant an expensive validation effort? After spirited discussions, the consensus to both questions was finally yes. The group concluded that experimental data would be valuable, but only if the model scale was sufficiently large, the model was very carefully constructed, and its elastic behavior carefully verified. The Maneuvering and Seakeeping Basin at the Naval Surface Warfare Center, Carderock Division was chosen for the tests. The tests are described in Section 3.2.2 of this appendix.

2 TECHNICAL ADVANCES

2.1 Key Issues

During the DARPA program that preceded the ONR S&T Program, two sets of model scale data were collected to validate existing hydrodynamic codes. The first data set modeled a serially aligned 3000-foot platform comprised of five *rigidly* connected semisubmersible modules (designed by Brown and Root). The second data set represented a serially aligned 5000-foot platform comprised of five *elastically* connected semisubmersible modules (designed by McDermott). All of the physical module models were intended to be essentially infinitely rigid. Both of those tests discovered torque sensitivity to relatively small near-beam waves, which resulted in greatly amplified connector loads that threatened the feasibility of both concepts. This amplification is a function of the specific flexibility of the connectors and the platform characteristics. Another more ominous observation was that the measured roll of the modules was not equal, which immediately established that the module models were actually elastic. This converts the problem from hydrodynamics to hydroelastics, and makes the data questionable because the module elastic response is important yet was not measured. See Appendix C, Section 3.2.1, for details. Finally, at the inception of this ONR Program there were only two known hydroelastic numerical models, and both were first generation and unvalidated.

Knowing the platform dynamics is critically important for many MOB design issues. For example, conclusions regarding the feasibility of MOB connectivity cannot be reliably made without accurate estimates of the global platform motions and associated forces between the modules. Accordingly, this S&T Program decided to invest a significant proportion of the funds to the advancement of hydrodynamic (including hydroelastics in this context) and structural analysis models. These models are integrally related in a number of ways. For example, the design of individual components such as connectors requires accurate structural modeling at the component, or *local*, level. The only numerically tractable approach for accomplishing this is to first model the overall, or *global*, motions and loads at the module level, then subsequently translate those global loads into an independent structural model of the specific component under study. There are a number of plausible mathematical approaches to accomplish this, each with their own balance of accuracy and numerical tractability. The objective of this Product Area was to identify and advance those approaches considered most applicable to the needs of MOB analysts, ranging from preliminary to final design, and operational to survival conditions. Existing finite element programs were considered sufficiently advanced for all of the structural modeling, but important gaps existed in predicting the hydrodynamic pressures and in interfacing this data with the corresponding structural programs. Those became the main developmental thrust of the MOB Design Tools Product Area, complemented by the need for associated validation data.

The dynamic analysis of conventional floating offshore structures in waves has typically been treated as a decoupled problem where the hydrodynamic and structural analyses are performed as two separate problems. This has been the routine practice for the oil industry when offshore floating production systems are designed as rigid structures. However, there are cases, such as the very long semisubmersibles modules for MOB, where this assumption is invalid, and it is instead necessary to solve both problems simultaneously. In other words, the deformation of the structure must be taken into account in the computations of the fluid motion around the body and the induced pressure forces on the body (i.e., it is a "coupled" problem). The term "hydroelastic" has been widely used for these types of problems where the flexible/deformational (as well as the rigid body motions) affect the wave field and

ultimately those same elastic body responses; hydrodynamics, on the other hand, is restricted to infinitely rigid bodies.

For a hydrodynamicist, the term "hydroelastics" refers to the satisfaction of the deformable body surface boundary condition of the boundary-value-problem for the velocity potential mathematical model. These problems can be accurately analyzed using linear hydroelastic codes based on the modal analysis approach where a basis vector set of *a priori* identified global mode shapes (typically, a finite number of bending and torquing modes in all degrees of freedom) are assumed. In the context of the MOB project, the term hydroelastics applies if the semisubmersible modules exhibit such elastic responses. Conversely, a MOB platform comprised of rigid (non-flexible) modules connected by ideal hinges or U-joints is not a hydroelastic problem since, mathematically speaking, these connectors act as simple constraints connecting the rigid bodies. This is a classic "multi-body" hydrodynamic problem, best interpreted as many adjacent modules rather than a single connected platform undergoing "hydroelastic" motions.

For preliminary analyses of long MOB platforms assembled from relatively long (nominal 1,000-ft semisubmersible modules), the multi-body assumption may yield reasonably useful initial estimates of overall motions. But for final design, hydroelastic effects will be significant so more advanced models must be used. A useful first observation towards selecting appropriate models was that the viscous forces imposed by the flow around the body would not be as significant as the wave-induced pressure forces. This observation lead to two important conclusions: (1) it was not necessary to resort to still-developmental computational fluid dynamics modeling, and (2) the problem instead could be solved by more mature potential flow theory (which inherently cannot handle viscosity). Accepting potential flow theory, along with other assumptions such as small amplitude motions and linear superposition of the structural deformations, allows for the use of three-dimensional hydroelasticity theory to estimate the global response of the flexible floating structure. Even these useful simplifications result in an intractably large computational problem when applied to a MOB-sized, multiple module, connected structure. So multiple studies were initiated, ranging from advancing commonly used low-order (constant) panel frequency domain models to higher order, to evaluating nonlinear, time domain models. These studies are described in Appendix C, Section 3.1.

As in most fields of engineering, naval architects and ocean engineers rely on both experimental and computational techniques to estimate wave-induced dynamics. Good analysts know that an important benefit from both approaches, especially the experiments, is that they often uncover unknown system behavior that was not anticipated. Computational tools, in the form of numerical methods and computer programs, provide designers with the capability to analyze proposed designs quickly and economically, and to search for optimum designs within a family of variants. Inevitably, however, these methods rely on simplifications of the overall physical problem, so their use introduces the need to establish exactly how much uncertainty remains. Physical experiments with small-scale models are commonly used to provide independent estimates. However, laboratory and prototype experiments can be costly and time-consuming, and carry their own set of uncertainties (due to, for example, scale effects). The usual approach to design is thus to use computational tools to the maximum extent that can be achieved, and to estimate their uncertainty by validating them with a limited number of high-quality experiments. The ONR MOB S&T Program followed this same approach, with experiments described in Appendix C, Section 3.2.

2.1.1 Hydrodynamic Model Advances

Computer programs based on the boundary integral method, or 'panel method', are widely used in offshore engineering to analyze the effects of ocean waves on various types of platforms and floating structures. The same programs can be used to analyze wave effects on MOB connected semisubmersibles, including motions, connector loads, and structural deflections of the modules. Other effects that can be estimated include local wave buildup under the superstructure leading ultimately to wave impact, which may be potentially severe, and the dynamic interactions with ships during cargo transfer. The capabilities of different programs vary, and at the inception of this Program none could predict all of the above effects precisely for a complex structure like a MOB, particularly in the more severe wave conditions it may experience. Thus, it was necessary to advance the capabilities of existing models, develop new models, and carefully validate them.

The principal numerical approximation for panel methods is the discretization of the structure's submerged surface, usually in terms of a large number of small flat panels, and the corresponding representation of the fluid pressure field on this (and often the free) surface. Two distinct questions must be answered before such models are used to simulate a real physical system, in this case the fluid motion and wave interactions with the MOB. First, are the theoretical assumptions of a particular numerical method valid for the physical problem, and second, how is a particular computer model best used. The first question can be indirectly answered by assessing published computations and experiments for similar systems, and directly answered by comparing calculated results to published benchmark computations for simple systems. This establishes an absolute reference. For diffraction theory and finite element structural models the second question is addressed by performing a numerical study of convergence versus discretization, which establishes the relative performance and stability of the model.

There is an ongoing debate regarding whether hydrodynamic interactions are important to MOB modules in waves. Sophisticated models assume full interaction between modules while simplified models neglect certain if not all modes of interactions. The computational burden associated with the sophisticated models can easily exceed one or more weeks for each trial combination of semisubmersible and platform architectures. If such interactions are ignored the analysis is greatly simplified, potentially allowing for a greater number of analyses, ultimately leading to improved platform dynamic characteristics and mission performance. However, the decreased accuracies associated with simplified models are not yet quantitatively understood over all of the design issues with unprecedented platforms like MOB.

It is known that interaction effects are particularly important for the relative motions of vessels in close proximity to a MOB, such as a ship or small boat alongside to transfer cargo or personnel. For these cases simplified models cannot be reliably used. Another topic of importance for MOB concepts with mechanical connectors is the simulation of connect/disconnect operations at sea. A full understanding of module behavior in close proximity during connecting and disconnecting operations is critical to MOB development.

The panel codes described above are based on the linearized potential theory, which assumes that the hydrodynamic forces and the motions of the structure are proportional to the incident-wave amplitude. There is broad acceptance for this approach in regard to the prediction of the dynamic motions of the overall structure. The validity of linearization is not so clear when the wave amplitude is sufficient to induce nonlinear effects such as breaking – in other words, in extreme storms. Therefore, nonlinear codes in the time domain must be developed or enhanced to address these issues.

Collectively, this Product Area initiated advancements on seven hydrodynamic/hydroelastic models that span the key analyses associated with MOB preliminary and final design. At first glance advancing this many models may appear overly exhaustive, until they are interpreted with respect to the many categorizations that apply: preliminary and final; linear and nonlinear, hydrodynamic and hydroelastic; time and frequency domain; and nonstationary and steady state. See Appendix C, Sections 3.1.2 to 3.1.4, and 3.1.6 to 3.1.7 for details. Lastly, a study is described in Appendix C, Section 3.1.1, that evaluated the not-trivial issue of how to properly apply existing diffraction theory models to analyze multiple-module, connected, MOB platforms.

For the MOB structural design problem, a finite element code (such as ABAQUS or ANSYS) is typically used to calculate internal material stress by post-processing the hydrodynamic/hydroelastic pressures and applying them to these detailed structural models. Current state-of-the-art finite element programs are fully capable of analyzing the MOB structural analysis problems. However, a universal pre-processing technique for converting pressures from hydroelastic models to the structural engineer's finite element model was not available at the inception of this program. This interface is a critical element for final design, particularly for the problems when hydroelastic effects must be considered. The MOB advancement in this area is described in Appendix C, Section 3.1.5.

2.1.2 Validation Data

Scale models of ships and offshore platforms are often tested in special towing tanks and wave basins. Waves generated by mechanical or pneumatic wave makers are directed toward the model, and its response characteristics are measured. For accurate results the waves must be accurately measured without interference by the model, and the walls and beaches of the tank or basin cannot reflect waves back toward the model. The large size of the MOB exacerbates these issues, even in the largest wave basins available, so experiments must be carefully planned and conducted.

As described in Appendix C, Section 1.2.2, the question of whether and/or how model scale tests would provide acceptably accurate data for the validation of MOB models was addressed during a 2-day workshop of internationally recognized hydrodynamics experts. Three test efforts were initiated.

The most extensive model experiments reproduced the motions of a hydroelastic MOB platform in waves. The objective was to gather accurate information regarding the connector loads for a hydroelastic platform. A 1:60 scale generic MOB platform architecture was used consisting of four semisubmersibles connected by pairs of stiff but elastic 3-axis cantilevers. The elasticity of the semisubmersible test modules themselves was carefully designed and constructed with the same resonant characteristics of the full scale modules, but with elasticity deliberately reduced to amplify the difficult-to-measure small model scale response. One module and two connected module tests were also conducted. Measurements included motions, connector forces, and the wave field. These hydroelastic tests were conducted at the Naval Surface Warfare Center Carderock Division (hereafter denoted NSWCCD), and are described in Appendix C, Section 3.2.2. This data has not been analyzed due to schedule and funding restraints.

The objective of the second set of tests was to measure wave-induced dynamics of a single semisubmersible at the deballasted draft, at zero and finite forward speed. This reproduces conditions associated with transit from one theater to another while the semisubmersible is riding with the pontoons at the surface. This is a difficult problem to mathematically model because the unsteady waterplane area associated with pitching, rolling, and waves overtopping the pontoons makes the problem very nonlinear. These tests were conducted in the towing tank at the U.S. Naval Academy (USNA) using a single, rigid

1:70 scale semisubmersible module. That data is being analyzed at the University of New Orleans. These tests are described in Appendix C, Section 3.2.3.

The objective of the third set of tests was to estimate the zero-speed wave amplification under the MOB at the operating draft. This is a critical concern because of the numerous types of large and small vessels involved with sea-based cargo transfer, and the need to provide adequate "freeboard" to avoid wave impact loads on the upper deck structure in storms. These tests were also conducted in the towing tank at the USNA using a single, rigid semisubmersible module; SAIC, Annapolis analyzed this data. These "air gap" tests are described in Appendix C, Section 3.2.4.

Lastly, the DARPA-sponsored tests at NSWCCD with three rigidly connected and five hinge connected semisubmersible modules were also analyzed, with awareness of the data limitations due to the unintended elastic response of the modules. Those studies are described in Appendix C, Section 3.2.1. The comparison between the data and results from available diffraction theory models was relatively good for the single module in waves. However, not unexpectedly, the comparisons were poor for the multiple module configurations.

Collectively, these data sets represent a wide range of important MOB functions. The data has been directly used to establish uncertainties associated with some of the newly advanced models, and it will be available for future validation efforts for the remaining models.

2.2 Major Products

The following tables summarize the major accomplishments achieved in the two technical thrusts of the Design Tools product area, namely, hydrodynamic models development/enhancement and validation data. The tasks are numbered per the Program Work Breakdown Structure given in the main text of this report. Section 3 of this appendix provides details on each of these specific products.

2.2.1 Hydrodynamic Models (WBS 3.1)

WBS	Task	Description
3.1.1	Identification of Analysis and Design Procedures & Evaluation of Existing Models	Assessment of existing hydrodynamic and hydroelastic models by benchmark analysis and validation procedures
3.1.2	Advanced Numerical Hydroelastic Model Development	Advance final analysis model HIPAN by adding hydroelasticity; improve WAMIT and HIPAN for computational efficiency; develop time-domain body-exact radiation program AEGIR.
3.1.3	Advanced Semi-Analytical Hydroelastic Model Development, MOBSHELL	Development of efficient computer model for simulating hydrodynamic multi-body interaction by adopting multiple scattering technique

3.1.4	Enhancement of the Large Amplitude Motion Program (LAMP) and Its Applications to MOB	Advance nonlinear water surface boundary condition for more accurate air gap prediction
3.1.5	Load Generator and Structural Analysis Interface, MOB-Hy-Loads	Develop algorithm to interface pressures from enhanced HIPAN to a finite element structural analysis model (for example, ABAQUS)
3.1.6	Connecting/Disconnecting Simulator, MOB_DYNSIM	Develop model to approximate wave-induced dynamics during connecting and disconnecting operations
3.1.7	Development of a Concept Assessment Computer Program, HydroMOB	Develop a Windows-based preliminary analysis model to assess MOB concepts for global response and connector loads (ignores hydroelastic effects and hydrodynamic interactions)

2.2.2 Validation Data (WBS 3.2)

WBS	Task	Description
3.2.1	Multibody System Response Study	Evaluation of DARPA MOB data
3.2.2	Hydroelastic Validation Model Tests	Dynamics of one, two, and four elastic semisubmersibles connected with elastic connectors
3.2.3	Transit Draft Dynamics Model Tests	Dynamics of deballasted semisubmersible
3.2.4	Air Gap Model Tests	Wave amplification below the MOB upper deck

The following conclusions were made by an outside reviewer* of the MOB Design Tools Advancements:

1. [A] quantum leap in hydrodynamic resources is required to achieve reliable and efficient design tools [for MOB]. Fortunately, this situation was recognized by ONR at the outset of the MOB Program. Substantial progress has been achieved, from the coordinated efforts of scientists and engineers from industry, universities, government research organizations, and the American Bureau of Shipping (ABS).
2. Substantial advances have been achieved with support from the MOB Program, to develop appropriate design. The risks inherent in designing a MOB have been greatly reduced as a result of this work.
3. Significant spin-off technology should also be noted, applicable to the design of ships and offshore structures.
4. Other fields where boundary-integral equations are used also benefit from the MOB Program. It is striking to note that the attention to fundamental computational problems has led to new techniques which apply to both MOBS and microfabricated sensors and actuators (MEMS), even though the length scales differ by a factor greater than a million!

* see Newman, J.N., DESIGN TOOLS—Appendix for MOB Assessment Report, Professor of Naval Architecture Emeritus, Massachusetts Institute of Technology, October 1999.

3 MODELS (WBS 3.1)

3.1 Hydrodynamic Models (WBS 3.1)

3.1.1 Identification of Analysis and Design Procedures & Evaluation of Existing Models (WBS 3.1.1)

3.1.1.1 Advancements

The overall objective of this work was to identify and assess design and analysis procedures and associated tools that will enable designers to develop safe and reliable Mobile Offshore Base (MOB) concepts. This required developing an understanding of the most critical conditions that affect the design of the MOB, and developing procedures to assess the adequacy of components for these conditions. It also required evaluating the utility of models for motions, forces and element stresses given payload, buoyancy, wind, wave, and current loads. The work was divided into three tasks.

1. Establishment of design and analysis requirements and procedures.
2. Identification and evaluation of hydrodynamic and hydroelastic computer models that were commercially available at Program inception.
3. Development and application of validation procedures for the identified commercially available software.

As detailed in Appendix D, all of the contractor architectures for the longest MOB platform length are built up using multiple semisubmersibles, maintained in a serial alignment with either: discrete connectors (such as a hinge or gimbal); long, elastic, buoyant truss/bridges; or simply a dynamic positioning system, with runway (not structural) continuity provided by short drawbridges. These concepts formed the foundation for the structural and other response issues that were addressed in this task. Structural design requirements and specific design cases were then defined by identifying and evaluating the many service conditions that would occur over the MOB's lifetime. Such considerations were used then identify the range of required simulation models.

Evaluation of the commercially available computer programs was divided into two parts: selection of the models, and evaluation using a benchmark analysis. The initial product evaluation included conducting a survey to identify software that can be used for MOB design applications. This step assessed the identified software based on vendor provided information, and recommended software candidates for a more detailed evaluation by performing a benchmark analysis. As a result of the initial product evaluation, twenty-five products covering six MOB analysis categories were originally proposed as potential candidates for various levels of benchmark analyses. However, only six hydrodynamic programs applicable to the deep draft analysis of wave load and motions were selected: AQWA, HIPAN, HOBEM, HYDRAN, MORA, and WAMIT.

A 3-module MOB structure was used for performing the benchmark wave dynamics analyses. The three modules utilized were identical, each 485 meters long and 120 meters wide. Each module consisted of two pontoons and seven columns per side, all rectangular in shape with rounded corners. The assembled platform was then approximately one-mile length. Three cases were considered in the analysis. The first case used a single module. The second arrangement considered three modules arranged in series without

any structural connection between any two adjacent modules. This arrangement represents a dynamically positioned platform or a platform just prior to connecting or immediately after disconnecting. The third arrangement considered three modules with a structural connector. The results of primary interest from these benchmark analysis comparisons included response quantities such as the first order loads and motions, mean wave drift force, free water surface motion, and fluid pressure on the wetted surface.

The six programs benchmarked for their capabilities for the wave load and motions analysis all use the diffraction/radiation approach. Among them, four programs, AQWA, HYDRAN, MORA, and WAMIT, use a constant panel method, while HIPAN and HOBEM employ a higher-order approach. HIPAN uses B-spline and HOBEM uses quadratic functions as a basis to fit both geometry and potential variation of solutions. This benchmark analysis indicated that the six hydrodynamic tools examined produce very similar responses of motions, mean drift forces, and air gap responses for the single rigid body case. This generalization holds true provided that the corresponding capabilities for the individual tool are available and that the numerical model (or mesh) used in the analysis is adequate. Similar motion responses for three-module motions were also found among HIPAN, HYDRAN, MORA, and WAMIT. Thus, the validation of one program's capability in predicting the hydrodynamic loads can be assumed to also be applicable for the other programs reviewed. WAMIT (version 5.4PC) was selected as the reference for these validation analysis.

As the result of this benchmark analysis, specific guidelines for the numerical modeling were developed to limit geometric modeling errors and hence the accuracy of the solution. A general convergence test is strongly recommended prior to all analyses, particularly when convergence test data on a similar structure are not available. In general, a finer mesh (i.e., more panels) is required in the areas where rapid change of gradients in the flow is expected, such as areas around the mean water level, corners, and intersections. For the MOB structure given in this benchmark analysis, a single module model (485 meters long and 120 meter wide) with 3,680 panels is good for MOB applications limiting convergence errors to within 2%. Some recommendations on software enhancements are also made for each hydrodynamic program.

The second task of this effort was the validation analysis. The objective was to assess the utility of the models in predicting hydrodynamic loads. To achieve this, key responses of interest for MOB applications were compared against those measured from an experimental test. A validation procedure was first established, consisting of the following steps.

1. Review and choose the most appropriate available experimental data.
2. Conduct a convergence test to determine an optimal numerical model for the analysis.
3. Simulate the experimental conditions in the numerical model(s), including body characteristics, wave frequency, and incident wave heading.
4. Compare the numerical versus experimental results, including statistical analyses to aid in quantifying any discrepancies.

The test data collected by NSWCCD under the previous DARPA program for a five-module, hinged MOB platform architecture was selected for this validation effort because the data included many aspects of primary interest to the MOB project. Even though there were concerns that the modules had unknown elasticity such that they were not as "rigid" as intended, the affect on the global responses was expected to be minimal. The responses of motion, mean drift forces, and connector forces were available from the regular wave tests. Data for irregular waves representing Sea States 4, 5, and 7 were also available. The five-module model was created to simulate the hydrodynamic performance of a 1500-meter long by 135-meter wide MOB. The individual semisubmersible modules were identical and each module consisted of

two pontoons and eight columns. The modules were connected in series, using a pair of hinge connectors between any two neighboring modules. No air gap responses were measured in the test.

Three MOB arrangements, namely single-, two-, and five-modules, were selected for this validation effort. The modules were assumed to be rigid. The single-module configuration involved 6 global degrees of freedom, while the two- and five-module configurations involved 7 and 10 global degrees of freedom, respectively. The seakeeping results for Sea States 4, 5, and 7 were of primary interest for comparison. The single-module tests involved head and beam waves. The two-module tests covered head, quartering, and beam waves. The five-module tests involved four headings. Connector and mean drift forces from the five-module test cases were also analyzed.

The single-module analysis results were, in general, in good agreement with the model test data over frequency and heading. In the two-module validation, the global motions were generally acceptable, except for some differences for the responses in head seas. Connector loads were not analyzed for the two-module case. The five-module case showed a poor correlation for motions for all headings. The head sea comparisons were the worst, with some improvements for quartering, and measurably more again for beam seas. While this task was not focused on correcting differences, the observation was made that this trend was consistent with differences in the hydrodynamic interactions among the modules and columns. The mean drift forces between the analysis and model test had significant differences with the exception of a few isolated cases. (Note that mean drift forces are second-order loads which are very sensitive to test conditions, hence they are difficult to predict.) Finally, the comparisons between the experimental and numerical connector loads were very poor, both qualitatively and quantitatively. This is undoubtedly due to the unintended elasticity of the modules, which (1) redistributes the connector loads as compared to a rigid body, but more importantly (2) shifts system resonances and hence overall system responses.

3.1.1.2 Products

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3.1.1.3 Resource

Bechtel National, Inc.; American Bureau of Shipping.

3.1.2 Advanced Numerical Hydroelastic Model (WBS 3.1.2)

3.1.2.1 Advancements

At the inception of MOB project, MIT had two particular hydrodynamic models of interest to MOB, namely, WAMIT and HIPAN. Both models are based on potential flow theory to provide frequency-domain solution to the large floating structure problems in waves. WAMIT is frequently used by the offshore industry in their offshore platform design but HIPAN is fairly new to the offshore community. WAMIT uses the so-called lower-order panel method that is a discrete boundary integral method, but includes hydroelasticity in the form of user-defined natural or mathematical mode shapes for the structure. The model has limitations to analyze very large size structures like MOB due to the computational burden. HIPAN was developed using a higher-order panel method. This method is numerically efficient and has important geometrical advantages, but this new model did not have all the features of WAMIT such as hydroelasticity. The objective of MIT's study was to develop robust and efficient computer hydroelastic simulation models for analyzing the seakeeping of very large offshore structures such as a MOB, by combining the hydroelasticity feature from WAMIT and higher-order panel approach from HIPAN and applying the pre-corrected-FFT accelerated equation solver.

In low-order methods the submerged surface of the floating structure is represented by a large number of flat panels and the velocity potential (or the source strength) is assumed piecewise constant on each panel. The potential is determined from an integral equation based on Green's theorem or is derived from the boundary condition on the structure. In such a lower-order panel method the integral equation is replaced by a system of linear equations with a number of unknowns equal to the number of panels. Computations based on lower-order panel methods have gained widespread applications among practicing engineers and hydrodynamicists for external-flow potential problems. In applications concerning wave loads and motions of offshore structures such frequency domain analyses are now routine. Despite the popularity and success of this technique, there are various problems where the computational burden is severe or where quantities such as gradients of the velocity field cannot be computed robustly from the conventional lower-order panel methods.

The use of higher-order panel methods can be applied to overcome these difficulties. Most of the higher-order methods are based on piecewise polynomial approximations of the geometry and potential on each panel. These approximations are normally restricted to linear or quadratic representations using local polynomials of first or second-degree, respectively. However, b-spline basis functions are used to represent the geometry and potential in HIPAN, which results in a more continuous representation of the structure surface and potential with greater geometrical flexibility and numerical efficiency. The efficiency of HIPAN is most apparent for relatively complicated structure shapes such as the proposed semisubmersible platforms for MOB.

In some applications nonlinear effects are important and must be modeled, particularly the second-order sum- and difference-frequency loads which occur at relatively high and low frequencies compared to the first-order incident wave spectrum. High frequency loads may be important depending on the resonant elastic periods of the body – such as a one-mile long MOB. Conversely, low frequency loads are important for rigid body motions where the restoring forces are relatively weak. Examples include the horizontal oscillations of moored and towed vessels, or dynamically positioned bodies in waves. The analysis of these second-order loads can be performed using a low-order panel method, but the computational burden is quite large and much care is necessary to ensure accurate results.

The hydroelasticity of WAMIT and higher-order b-spline basis of HIPAN were mated to produce the enhanced HIPAN Version 2.0.4 that was released in February 1999. The development of HIPAN 2.0.4 offers the much-desired features of computational efficiency and analysis capabilities necessary for MOB.

Despite the fact that higher-order element code HIPAN 2.0.4 has shown more than one order of magnitude in efficiency over the low-order panel method used in WAMIT, MIT conducted an extensive research in developing fast solution techniques in order to accelerate both models. FastWAMIT was successfully developed using the precorrected-FFT technique. This program is able to solve hydrodynamic problems on the scale of a MOB with reasonable computational efficiency (but somewhat tedious process of discretizing the body using the low-order panels). However, the development of FastHIPAN was not considered complete, based on observed conditioning and convergence problems associated with the higher-order basis function representations.

The importance of acceleration algorithms is highlighted in Figure C-1 below. The left subfigure shows a characteristic mesh for a MOB conceptual design, along with a comparison of run-times vs. error for the low- and high-order, linear, frequency-domain codes in the right subfigure. The "pFFT-" prefix denotes the version with the pre-corrected FFT equation solver. *For nominal MOB platform architectures which must be analyzed for typically fifty or more frequencies and a half dozen headings, the accelerated algorithms reduce simulation times from months to hours.* This enormous reduction in simulation times will translate to reduced project costs and improved designs by allowing for more thorough examination of alternatives before construction.

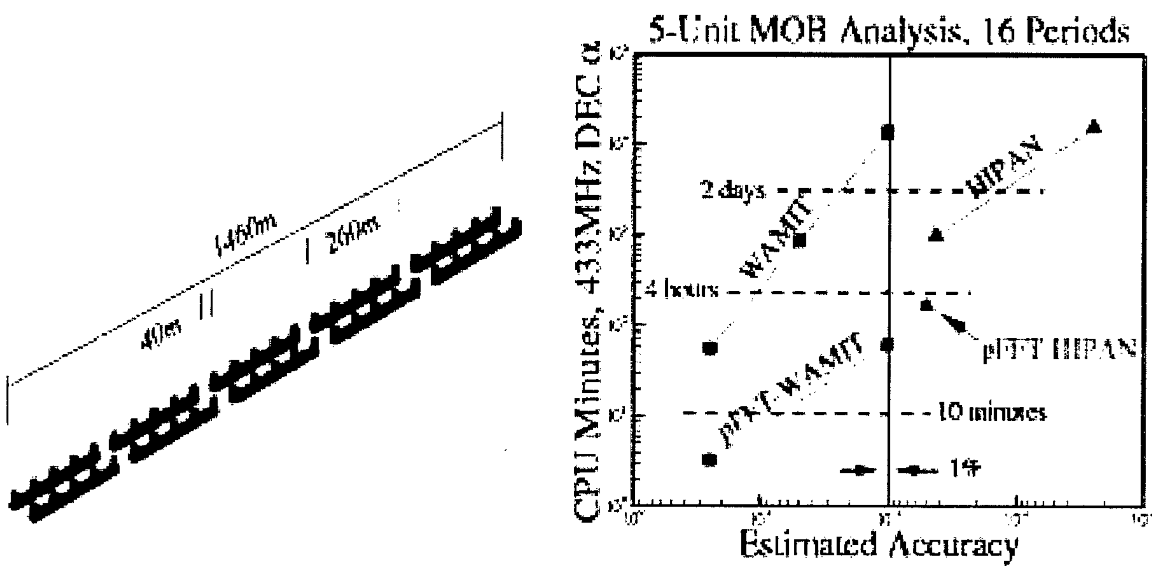

Figure C-1. Representative computational advances made in WAMIT and HIPAN.

Precorrected-FFT acceleration has also been applied to a higher-order, nonlinear, time-domain, Rankine boundary element method called AEGIR. This model allows for a nonlinear free surface boundary condition (within the restriction to inviscid flow inherent to potential theory) and can satisfy exact body boundary conditions. This model has a great deal of potential for computationally efficient and accurate simulations, but it is still in a research phase and its present development includes the radiation response only. To become a full seakeeping code the diffraction problem and higher-order acceleration for the

fully nonlinear problem are both necessary; hydroelasticity would follow much later. Figure C-2 is an example of AEGIR results, showing the body-exact simulation for a MOB radiating heave waves in otherwise still water. The computational run-times and memory requirements are included. Acceleration allowed the simulation to fit in memory on an existing workstation and reduces the total run-time from the impractical 2.5 months to the more reasonable 42 hours.

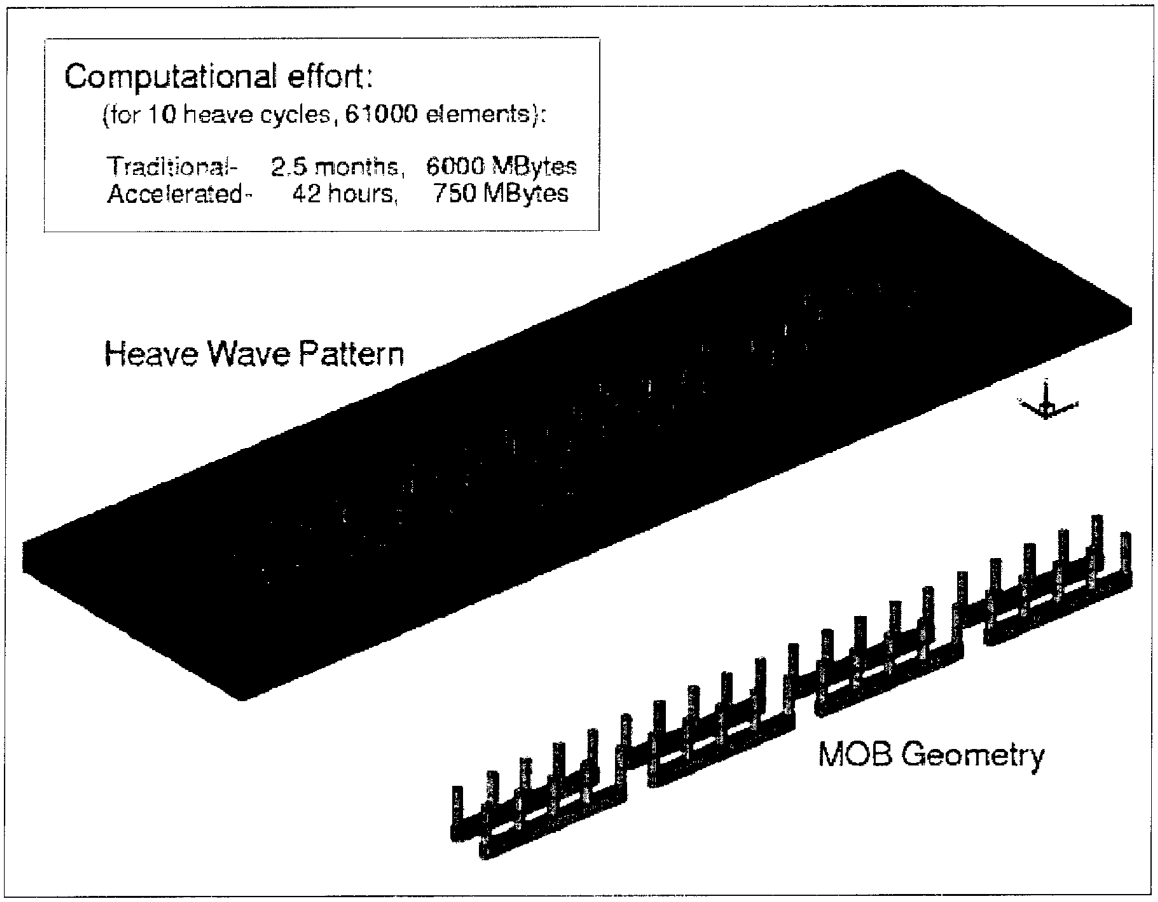

Figure C-2. Example AEGIR results for the heave-induced radiative wave field around a generic MOB platform.

In advancing these two hydroelastic codes, MIT teamed up with AeroHydro, Inc. (AHI) to develop supporting utility programs for preparing input data, analyzing and displaying output results, and postprocessing. Specifically, AHI developed and provided a Relational Geometry library (RGKernel) and supported its integration into both models. Relational Geometry is a proprietary technology developed by AHI, which facilitates creation, analysis and optimization of multi-surface geometric models and parametric variations on these designs. General improvements were made to functions for b-spline surfaces, which became critical since HIPAN geometry is restricted to b-spline surfaces. AHI also developed NBS2HIP utility, which converts a standard MultiSurf output file (NBS format) to HIPAN input data. HIPAN models are created with MultiSurf and NBS2HIP.

AHI's MultiPanel is a visual utility for displaying and debugging discretized geometry for hydrodynamic codes, and for visualizing computed results in the form of surface distributions such as pressures, velocities, and singularity distributions. MultiPanel was extended to display HIPAN input geometry and computed surface pressures. HIPAN results are in the form of b-spline distributions rather than piecewise constant distributions. An animated display was developed which presents a "movie" of color-coded surface pressure as a function of time.

AHI also developed the postprocessing capability that contributes to the linking of hydrodynamic results with finite element structural codes (see Appendix C, Section 3.1.5). Two utility programs, XYZ2NUV and HIP2FEA, were developed to calculate point pressure or load data required for finite element analysis. Given a file tabulating the X,Y,Z positions of FEM nodes and/or integration points, where point pressure or load data is required, these two programs will relate the X, Y, Z positions to B-spline surface and output the pressure or load.

3.1.2.2 Products

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3.1.2.3 Resource

Massachusetts Institute of Technology (MIT); AeroHydro Incorporated (AHI).

3.1.3 Advanced Semi-Analytical Hydrodynamic Model (WBS 3.1.3)

3.1.3.1 Advancements

The wave-structure interaction typical of very large floating MOB platforms is complex. Because the approach described in the previous section based on a complete diffraction analysis of the fully assembled platform is very computationally intensive, it was considered worthwhile to evaluate an alternative and potentially more efficient method based on a "semi-analytical" approach. Achieving this work required two major software components. The first component was a standard linear diffraction/radiation model. This model is used to compute the basic diffraction characteristics for one rigid module rather than the entire platform, and accordingly is significantly faster. The second software component is the key. This model starts with the previously-computed diffraction results [for each module type], and uses a multiple scattering technique that takes into account the interaction effects among any number of modules in any arbitrary arrangement. Thus, this second model uses linear superposition of the incident, radiated, and diffracted waves for all of the modules to obtain a convergent solution.

This approach is computationally much more efficient than solving the complete hydrodynamic problem consisting of all the modules. The only tradeoff is a small decrease in accuracy associated with truncating the iterative solution process. The principle application of this approach is for multiple analyses of alternative platform configurations for a given module; in other words, the number of modules, connectivity, and arrangement can be quickly assessed using the same precomputed data file of basic hydrodynamic characteristics for one (or more) module. This approach also makes all parametric studies very efficient for assessing variations in the module for a given platform architecture, including module length and beam, draft/payload, number and shape and diameter of columns, etc. Subsequent studies would then apply a hydroelastic model to get more accurate responses, particularly connector loads. The model can also be used quite effectively for studies of the interaction between a MOB semisubmersible and ships berthed alongside. Finally, this model also includes an optional analysis feature; for the rare case of a large number of semisubmersibles with the same geometry such as floating cylinder group, analytical approximations are available using an inner and an outer region to get the response.

A computer program MOBSHELL was developed based on the lower order boundary element method to compute forces, motions, connector loads and steady drift force on a multi-module floating structure in regular waves. Reports on the theory and user and program guide were prepared. The program, which consists of three program modules: NBODY, DIFFCOEF, and MULTBODY, is an excellent tool due to its efficiency. However, the interface between this hydrodynamic model and the finite element structural model was not developed.

3.1.3.2 Products

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3.1.3.3 Resource

Offshore Structure Analysis, Inc.

3.1.4 Enhancement of the Large Amplitude Motion Program (LAMP) and Its Applications to MOB (WBS 3.1.4)

3.1.4.1 Advancements

The previously-described seakeeping models, for both rigid and elastic bodies, include among their mathematical assumptions the requirement for small wave amplitude. This does not introduce any significant errors in the predicted response if the waves are small or even moderate in size. However, this approach does not represent the true physics of a body moving in large waves, as exemplified by the dynamics of a small vessel as its bow and stern plunge through and into wave crests. At the inception of this Program there was only one hydrodynamic model capable of modeling extreme motions - the Large Amplitude Motion Program (LAMP). The computational efficiency of LAMP had recently been advanced with a new approach based on an inner/outer region matching technique. This made the model numerically tractable for simulating the dynamics of a single MOB semisubmersible, yet it was unproven. The objective of this study was to evaluate the utility of the new LAMP for a number of MOB platform design and operation problems.

LAMP is a general-purpose computer code for large-amplitude ship/platform motion simulations and wave load predictions. It is an inviscid flow model that uses a time domain diffraction theory approach to track the instantaneous position and orientation of the vessel versus the free surface. The LAMP system has been under development for over ten years in order to provide physics-based calculations of the motions and loads for ships in extreme sea conditions. Under the support of this Program, LAMP was greatly enhanced for application to large floating platforms. Two particularly important enhancements were completed: (1) advancement of the nonlinear wave surface boundary condition in the LAMP formulation, and (2) implementation of multiple body dynamics for studying ship-platform and platform-platform interaction problems.

The original LAMP development was developed mainly for more accurate prediction of platform motions and wave loads, especially in extreme sea conditions. For this purpose, the original LAMP formulation, in which the free surface solution was linearized about the *incident* wave surface, was adequate. For MOB however, it was felt necessary to model the *instantaneous* free surface around the semisubmersible, which, in addition to the already accounted-for incident wave profile and instantaneous position and orientation of the platform, required an advance to account for the radiated and diffracted waves due to the body. These advancements to the [nonlinear] free-surface boundary condition were expected to greatly improve the accuracy of the local wave field for design issues such as the air gap in extreme seas.

The LAMP formulation at Program inception used a perturbation method to transform the nonlinear problem into separate linear problems. In the perturbation method, the quantities related to the velocity potential, the free surface elevation, and the body motions are expanded as perturbation series with respect to a small perturbation parameter. By substituting the perturbation series into the governing equation, body boundary condition, and free surface boundary conditions, the original nonlinear problem can be recast as separate linear problems to different orders of the perturbation parameter. The linearized free surface boundary conditions can further be expressed with respect to the undisturbed free surface using the Taylor's expansion. LAMP solved the perturbed problem up to second order, and results compared well with an alternative "Mixed Eulerian Lagrangian" approach (presently under development at MIT by Professor Dick Yue).

The MOB-enhanced LAMP code has the capability of computing the complete local wave field using

both linear and nonlinear free surface boundary conditions. It can also separately compute the disturbance wave fields due to radiation (body motion) and diffraction (wave-body interaction), which can help in determining the relative importance of each component in the air gap computation. In particular, the importance of body motion on the local wave field can be examined. For example, various specialized body configurations (e.g., columns or pontoons only) have been computed to study the effects of the various components on the wave field. The results have been compared with those obtained from other linear codes in order to evaluate the importance of nonlinearity and the consistency between different computational approaches. Sample results of the surface wave profile using both linear and nonlinear free surface boundary conditions are shown in Figure C-3 below. The color green denotes the still water level, while red corresponds to crests, and blue to troughs; color intensity reflects amplitude. As can be seen, the nonlinear prediction shows more detail in the local wave pattern.

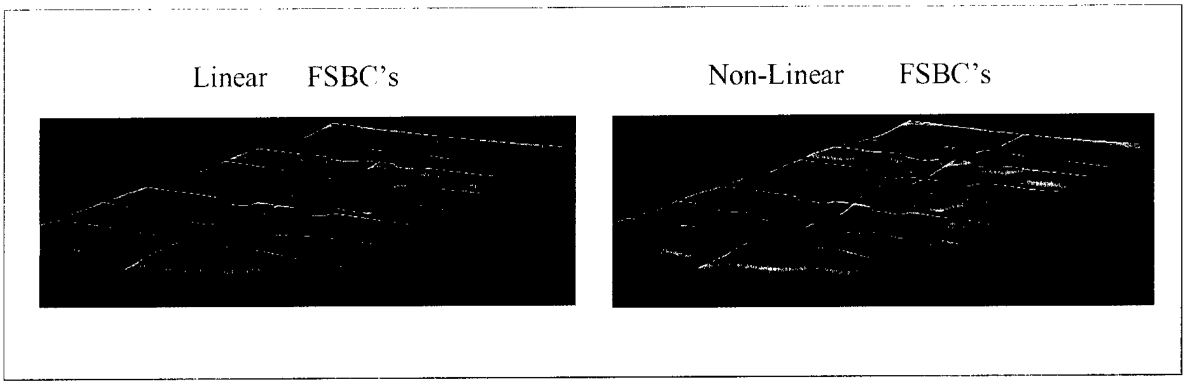


Figure C-3. Linear and nonlinear wave fields from LAMP.

For normal operating condition, a MOB will be operated in the open ocean. Although it is mobile to a degree, it must be expected that MOB will encounter severe weather conditions. In these conditions, the modules are usually disconnected. Accurate predictions of extreme loads are important for structural integrity in such survival conditions. Typical storm waves have wave periods from 12 to 18 seconds; this corresponds to wavelengths from 220 to 500 meters with maximum wave height up to 30 meters. The motion and loads of a module in this case can be very large. The enhanced LAMP code has been used successfully to assess the nonlinear motions and loads of the MOB platform in deep draft conditions of individual modules. Computations were performed at zero speed of the module in various wave directions. Storm sea conditions represented by both regular wave and random wave (generated from a specified spectrum) were considered.

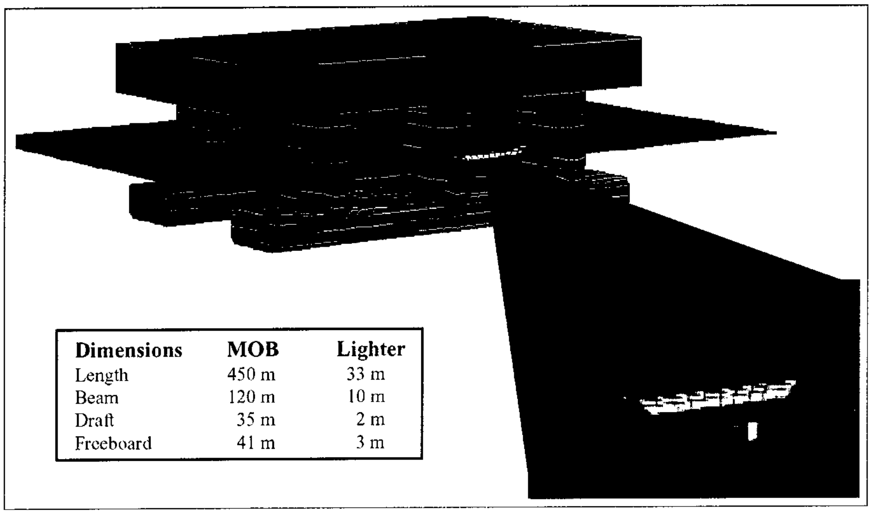
The next case examines a MOB in transit mode, where the module is floating on the two pontoons (shallow draft). These cases are of interest because: (a) some transits would include a large preloaded payload, and at the shallow draft this payload would create a high moment arm and associated high inertial loads, and (b) time criticality would require transits regardless of the prevailing intensity of the seas along the transit route. MOB operators and planners must have access to reliable models of the effect of these factors on the module dynamics, payload accelerations, and module stability in order to optimize such transits. It is well know that the wave-induced structural loads may be very nonlinear for semisubmersible in these cases, which excludes the use of frequency domain hydrodynamic models and makes LAMP the only viable model. Representative computations were performed for a generic module design versus speed of advance, and wave frequency and direction. Storm sea conditions were represented by both regular wave and random wave (generated from a specified spectrum). Relative

motions between the pontoons and the wave are available to assess the occurrence of slamming on the pontoons and other structural members. However, local slamming and the high-frequency whipping responses were not examined.

The MOB-enhanced LAMP was also used to provide support in planning the air gap experiment conducted at the United States Naval Academy (USNA). Specific details about the test can be found in Appendix C, Section 3.2.3. Air gap computations of the USNA MOB model were performed in the operating condition (deep draft) at zero speed in various wave conditions. Computations were carried out using linear and nonlinear free surface models for both constrained and unconstrained cases. Recommendations were made concerning the testing priority of MOB operating and wave conditions and for the placement of wave probes under the MOB deck structure. During the tests, the LAMP air gap predictions were available for immediate comparison with the experimental measurements such that the collection of quality data could be assured. The availability of these results was also used to identify optimum probe locations where wave amplifications could be large. Comparisons of pre-computed maximum wave contours to the observed wave phenomena indicate that the variation of the areas of maximum wave amplification with wave period was qualitatively well predicted. This enhanced LAMP clearly demonstrated the effectiveness of using numerical tools to design an experiment.

A limited validation between the air gap predictions by the enhanced LAMP and the USNA air gap data was performed. Ten linear and nonlinear LAMP air gap results were analyzed and compared with corresponding cases of the experimental measurements. Six comparisons were done where the module was constrained (i.e., wave field rather than air gap validation). Although the nonlinear LAMP predictions in general gave the right trend and reasonable quantitative results, these comparisons showed that the linear LAMP predictions under-predicted the wave amplification as the incident waves became steeper. One indirect conclusion from this is that the small-amplitude frequency-domain models would show even greater errors. Four additional comparisons were completed that focused on the ability of LAMP to simulate the air gap; this requires accurate modeling of both the wave field and the module motions. Results for unconstrained module motions in both head seas and oblique seas showed major differences. This was unexpected, and was attributed to the fact that the inviscid LAMP formulation could not damp out a transient responses at natural frequencies for heave, pitch, etc. Further study in this area is required.

The second enhancement to LAMP was to implement the capability of multiple body dynamics for studying ship-platform and platform-platform interaction problems. The original LAMP System computed the motions of a single ship or platform moving as a rigid body in a seaway. However, a MOB may consist of a series of platforms that move independently yet interact hydrodynamically and/or structurally. Furthermore, the interaction between a platform and a ship operating alongside may be important for cargo transfer operations. With these modifications, accurate three-dimensional hydrodynamic interaction effects can now be considered in the LAMP framework. A sample example, where a lighter parked next to a module in beam waves, is shown in Figure C-4 below. In this example, the radiation and diffraction wave field created by the platform greatly influences the motion of the lighter.



Dimensions	MOB	Lighter
Length	450 m	33 m
Beam	120 m	10 m
Draft	35 m	2 m
Freeboard	41 m	3 m

Figure C-4. Sample LAMP geometry for multiple body simulation.

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3.1.4.3 Resource

SAIC Ship Technology Division.

3.1.5 Load Generator (WBS 3.1.5)

3.1.5.1 Advancements

Because of their unprecedented size and nature, the analysis of MOB platform responses is challenging and often exceeds the limits and assumptions of traditional analysis methods. Analyses must accommodate the large scale of these structures, the use of novel components (such as nonlinear connectors which offer desirable behavior for high sea states), and the need for long term reliability and operability over a wide range of conditions.

The simplest "frequency/frequency" approach employs a frequency domain, three-dimensional, linear hydrodynamic model for the hydrodynamic loads, followed by a structural analysis using a finite element model, still in the frequency domain. However, this traditional approach using linear hydrodynamics and linear structural responses precludes consideration of nonlinear structural effects such as plasticity or energy absorption through inelastic members (e.g., fender impact). The most accurate "time/time" approach would use a fully integrated hydrodynamics/structural analysis model in the time domain; however, such models are only in a preliminary research phase and are presently too computationally intensive for routine use.

Instead, a compromise "frequency/time" approach was selected for MOB advancement. This hybrid, decoupled approach assumes that the overall structural elastic deformations of the body are small (compared to the rigid motions) such that a linear hydrodynamic or hydroelastic frequency domain model can be used to estimate *global* wave-induced responses. These are then used in a nonlinear structural analysis time domain model that allows for *local* nonlinear structural responses (e.g., plastic failure of a particular flange that does not greatly affect the overall rigidity of a module). This does require some iteration during the structural analyses as explained below.

McDermott Technology, Inc. (MTI) advanced this methodology and developed the associated software tools called MOB-HyLoad. Broadly speaking, this model couples MIT's linear, frequency-domain hydrodynamic analysis model HIPAN to the nonlinear, time-domain, finite element structural analysis model ABAQUS. Three levels of structural modeling capabilities were developed that span the complete range of analysis requirements from preliminary to final design.

The most accurate model is a shell finite element structural model that can incorporate distributed loads, local flexibility, and hydroelastic effects - but at the expense of long calculation times. The typical shell model is a relatively detailed 3D representation with contoured surfaces and structural properties that accurately represent *local* geometry and global stiffness and mass characteristics. This level of detail makes this type of model the likely model of choice for final structural analysis during a MOB design process.

The simplest of the three models uses a lumped mass approach. Serially connected lumped masses are used to represent the MOB modules while the interconnectivity properties were represented by spring and damping systems. This simple, *rigid body* model was developed in order to provide first order approximations of *global* motions and connector loads; the hydrodynamic excitation is integrated over the hull to yield equivalent forces and moments at the centers of mass. This model runs more efficiently than the shell model, and allows for rapid screening of various connector designs. However, the simplicity of this point mass model precludes the ability to incorporate distributed hydrodynamic loads or hydroelastic effects. Therefore, this model will generally be restricted to use as a screening tool and for providing a

relative comparison for various design options. It would not be appropriate for use in qualifying a structural design.

The third, intermediate model uses beam elements for the modules that can incorporate distributed loads and the module flexibilities associated with hydroelastic effects. This beam element model can be executed much faster than the shell model while still estimating the *global, hydroelastic* major loading and response effects. The hydroelastic excitations for this model are integrated over the length of the actual wetted column/pontoon surface to yield equivalent [uniform] beam loadings.

The basic Hy-Loads software package is shown in Figure C-5 and described next.

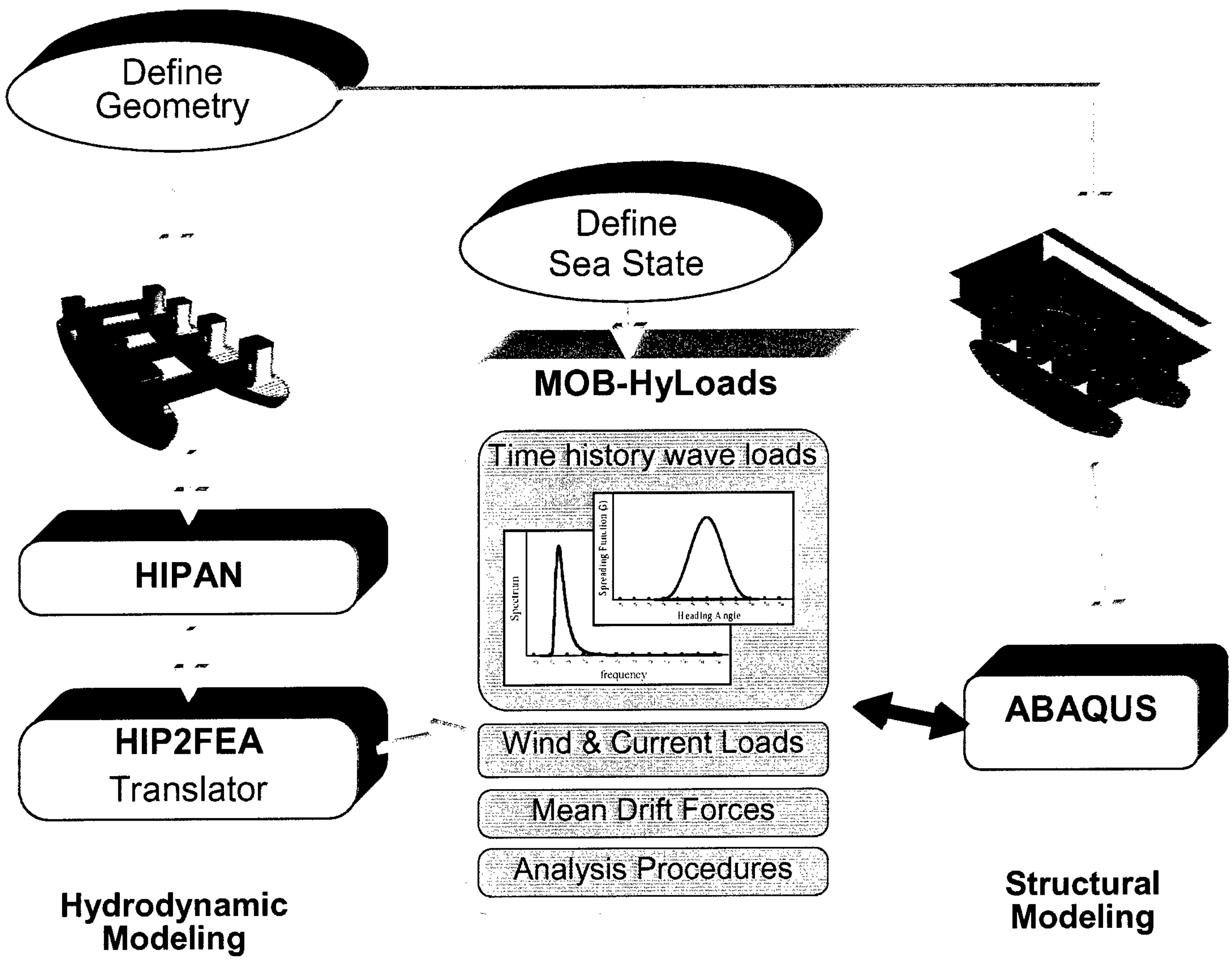

Figure C-5. MOB-Hy-Loads Functionality

The methodology adopted in all three Hy-Loads models assumes linear hydrodynamics. HIPAN, described in Appendix C, Section 3.1.2, is used to determine the hydrodynamic diffraction forces and the hydrodynamic coefficients (added mass and radiation damping) for the rigid as well as elastic module responses. The b-spline basis functions used in HIPAN allow for a continuous representation of the pressure over the wetted surface. This is a key aspect of the Hy-Loads package. This feature allows the structural user complete freedom in choosing an optimum finite element mesh because the Hy-Loads model can extract pressures for any arbitrarily-configured element geometry. *Thus, Hy-Loads acts as a universal translator of hydrodynamic pressures into the equivalent surface loading in the finite element shell model.*

Normalized diffraction forces and radiation coefficients are calculated for a range of periods and headings that cover the sea state of interest, and moved into a Hy-Loads file. The diffraction forces are known *a priori* based on the incident waves, and thus can be directly applied in the structural analysis. However, the radiation forces depend on the present and past rigid and elastic structural responses of the MOB modules via convolution integrals and impulse response functions for each structural surface element. Since the nonlinear connectors influence the motions of the MOB modules, these forces are coupled with the time-domain responses. The finite element program ABAQUS is used to calculate the time-domain structural response of the MOB. To simulate realistic ocean waves, a sea state is then used by scaling these diffraction and radiation forces with wave spectrum and spreading functions, where the contributions from the different wave periods and headings are added with random phases.

When hydroelasticity is important in the analysis, HIPAN's generalized modes solution technique is used to determine the diffraction forces (pressures) and the hydrodynamic coefficients (added mass and radiation damping) for the MOB. Diffraction forces are calculated for a range of periods and headings that cover the sea state of interest. The hydrodynamic coefficients are calculated over a large range of periods, to properly characterize the necessary impulse response functions. However, in order to minimize the number of impulse response functions, the radiation forces are calculated as modal quantities and distributed over the wetted surface as pressures. MOB-Hy-Loads then uses the generalized modes of the structure to evaluate the radiation forces. The radiation forces are obtained from the convolution integral of the impulse response function with the modal velocities. These forces are treated as external forces (pressures). The diffraction forces are directly applied as pressures on the structures. A dynamic analysis of the nonlinear structure subjected to the hydrodynamic wave forces is performed using ABAQUS. At each time step, the deformed shape of the structure is decomposed into its modal contributions and the appropriate loads applied to the model. The problem is then iteratively solved at each time step, since the radiation forces depend on the current deformation of the body. An assumption inherent in this method is that the hydrodynamic loads on the structure can be accurately predicted using linear hydrodynamics. All other effects such as structural nonlinearities, frequency dependent added mass and radiation damping, and hydro-elasticity are accurately modeled.

3.1.5.2 Products

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3.1.5.3 Resource

McDermott Technology, Inc.

3.1.6 Connecting/Disconnecting Simulator (WBS 3.1.6)

3.1.6.1 Advancements

Maneuvering extremely large floating MOB modules in close proximity during the open ocean connect/disconnect operation, or for purposes of otherwise maintaining module relative position, is one of the most critical operations involved in the MOB concept. In fact, the operational scenario for the disconnect operation calls for it to be carried out in an elevated sea state. In such connect/disconnect operations, the momentum and inertia associated with large and heavy modules and the advance speed of are tremendous. The threat of impact and associated damage to modules during these operations poses a serious problem that needs to be properly investigated as a possible condition that drives the connector design. The primary concern in the case of such operations is the wave-induced motions (or relative motions of adjacent modules) since these motions, in the case of such large structures, is most likely not controllable in an active sense.

Modeling this connect/disconnect operation is not trivial. First, it is not steady state, which immediately requires a time rather than a frequency domain model. Second, the inertial characteristics of the system change abruptly in a fundamentally way for connected versus independently floating modules (before/after the event). Third, if impact between two modules does occur it is highly nonlinear.

A computer program called MOB DYNSIM (MOB DYNamic SIMulation) was developed to simulate the dynamic behavior of multiple arbitrary bodies in regular and random waves in the time-domain. Rigid bodies are assumed, and regular or random waves are allowed. In addition to waves, the motion of the system of bodies may be initiated by setting any type of initial offset of the bodies. Hydrodynamic interaction between adjacent (but not distant) modules of the MOB structure is included.

MOB_DYNSIM is based on the impulse-response approach. The analysis is carried out in two parts, a frequency-domain analysis which is used to compute basic (frequency-dependent) hydrodynamic coefficients, followed by a separate time-domain analysis which utilizes the frequency-domain results. This sort of two-part analysis is convenient from a computational viewpoint since it allows the time-consuming calculation of the hydrodynamic coefficients to be pre-computed so that the time-domain calculations can be carried out very efficiently by a postprocessor, typically considerably faster than real time. It is for this reason that this indirect approach was favored over the direct use of the panel method based on the time-dependent Green's function. In the case of large problems the latter approach tends to be very computationally intensive and occasionally unstable. Moreover, it is the intention to develop a computationally efficient method that could be extended to study such operations as connecting or disconnecting modules in a seaway and efficient, robust methods for use in design studies.

The three-dimensional hydrodynamic analysis consists of two tasks. The first evaluates two sets of frequency domain hydrodynamic coefficients of added mass, radiation damping and wave excitation loads associated with: (1) a single module in isolation and (2) the supplemental hydrodynamic interaction between adjacent modules. Using frequency domain coefficients assumes that the mean spacing between the modules remain relatively constant during the analysis (otherwise the interaction effect would vary). These coefficients are then used as a basis for convolution operators in the time-domain dynamic simulation. The approach is shown to be an accurate and practical and does not preclude the extension to the inclusion of drift forces, an option that is lost in the case of frequency-domain methods based on the Haskind's relations approach.

The application of MOB_DYNSIM is not limited to only the in-line MOB configuration or modules of identical shape or mass properties, etc. The program can be applied to solve the problem of a number of bodies whether they are similar bodies or not, or whether they have any planes of symmetry or not. The program is therefore applicable, for instance, to a ship along side a multi-module MOB as well as a MOB platform during connecting/disconnecting.

3.1.6.2 Products

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3.1.6.3 Resource

C.J. Garrison & Associates.

3.1.7 Development of a Concept Assessment Computer Program, HydroMOB (WBS 3.1.7)

3.1.7.1 Advancements

As described in the main body and Appendix D of this report, the most likely design for a multi-module MOB involves three to five semisubmersibles, each approximately 300 to 500 m long, connected serially. The connection could range from a pseudo-connection, where the modules are aligned solely by dynamic positioning, to mechanical connectors that would enforce alignment via large forces transferred through the connectors. In order to obtain an optimal design by exploring various innovative alternative concepts, one can imagine that there are many ways of forming a MOB made up of many modules. To determine the best possible configuration for given sea states, one needs an effective and efficient tool to estimate global dynamic responses (relative and absolute motions, and connector forces) of different platform architectures. Use of a 3- dimensional hydroelasticity theory, which includes the full interaction between different modules, would be an enormous task for each of the configurations studied. Needless to say, if one chooses this route during the conceptual design stage, only a small number of configurations can be analyzed and at great cost and time. That is why it is necessary to have an efficient tool to analyze quickly various module configurations.

Once a new type of MOB is developed, one needs to determine whether the MOB has acceptable stress or motion responses. A major emphasis of this work was then focused on developing a tool to enable designers to efficiently understand the response behavior of a MOB in waves, especially as to how the different parameters affect the connection forces, and how these forces can be reduced through design.

Typical analyses for evaluating the motion performance of the MOB based on a 3-D linear panel method require several steps. These include (a) generate the panels, (b) calculate the mode shapes of the structural eigenvalue problem, (c) calculate the generalized hydrodynamic loads, (d) solve the equations of motion to determine the principal coordinates, and (e) obtain the motion response and stresses in physical coordinates. However, if the layout of the MOB is changed, one must repeat the procedures from the beginning. The above steps are applicable when one uses the 3-dimensional hydroelasticity theory, which includes the full interaction between the different modules. Such calculations would require enormous amount of computational resources for each of the configurations studied because of the large number of panels. Needless to say, if one chooses this route during the conceptual design stage, only a small number of configurations can be analyzed and at a great cost and time.

The experience from studies of very large floating structures made up of semisubmersible modules indicates that, if the modules are sufficiently far apart, it suffices, for initial screening purposes, to neglect the full interaction between the modules. The hydrodynamic calculations can be done for each module as if the other modules are not present. Moreover, if the local deformations of the modules are not expected to be very "large", the modules can be treated as "rigid" rather than flexible.

With these two key assumptions, a stand-alone Windows-based program called 'HydroMOB' that can run on PCs running Windows 95/98 was developed. HydroMOB consists of a graphical user interface (GUI) and hydrodynamics engine. The HydroMOB GUI works as pre- and post-processor with several features. They include (a) generate multiple MOB modules and panel meshes, (b) input the layout of module positions in the plan view, and connector properties such as locations and stiffnesses, (c) specify wave spectra, and (d) visualize the motions and connector forces. The hydrodynamics engine is HYDRAN-MOB, which is a typical frequency-domain hydrodynamic program based on the linear potential theory

developed by OffCoast, Inc. A HydroMOB sample GUI screen is shown below (Figure C-6).

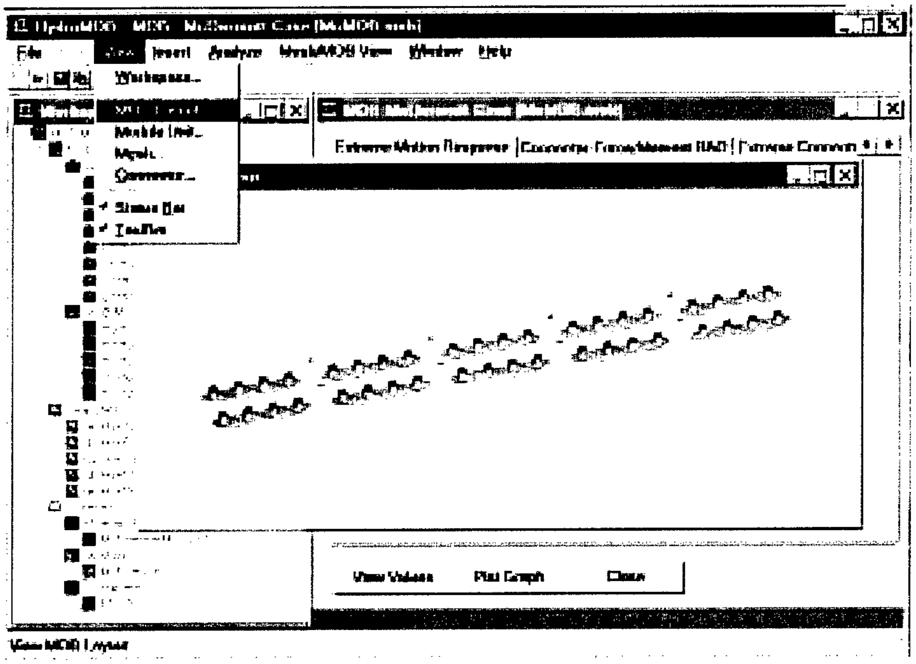

Figure C-6. HydroMOB graphical user interface example.

HydroMOB is a user-friendly, graphically based computer program, based on simplified analysis assumptions, which can be used to evaluate at the conceptual design level a large number of alternative MOB configurations. It was developed because at the inception of this Program , there were no known tools that had the capability of evaluating alternative MOB concepts efficiently. Although focussed on the MOB, in terms of ease-of-use and its graphical user interface, this tool represents a significant advancement of current commercially available tools for the hydrodynamic analysis of even single rigid body.

In HydroMOB, the hydrodynamic analysis is made such that the hydrodynamic interaction between modules is neglected. The impact of this assumption should be investigated before HydroMOB is used to evaluate any design concept. To illustrate this, test runs were made for a 5-module, 1500m MOB structure (shown in Figure C-6 above), where full hydrodynamic interaction between modules was considered by using the computer program HYDRAN. Each module two-pontoon, eight-column module was 300 m x 152 m x 69 m, with a mass of 3.37×10^8 kg. The modules were arranged serially and connected by flexible connectors. The wetted surface of each module was discretized with effectively 1,616 constant-strength panels for a total of 8160 panels for the entire MOB (although double symmetry was utilized to reduce the actual number of panels to 404 per module). The response was determined in the frequency domain for 29 wave frequencies and for 9 wave headings, varying from 0° to 90°. The motion results without interaction from HydroMOB are shown in Figure C-7 below along with those with interaction from HYDRAN. The agreement in lateral motion is good. The vertical motions also agree well except in the head-sea case, where the difference is up to 20%. The agreement between HydroMOB and HYDRAN was better for the connector force. All of the force components were matched perfectly

except at around the head sea case, where the connector force was not so significant. As an aside, note also the sensitivity of the forces to near-beam on waves (in this case around 85 degrees).

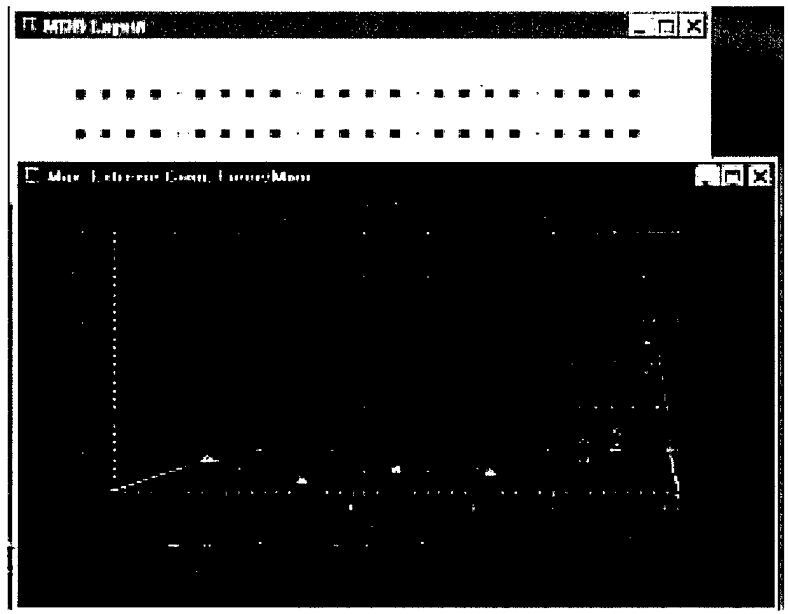

Figure C-7. Representative connector forces versus incident wave direction.

3.1.7.2 Products

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3.1.7.3 Resource

University of Hawaii at Manoa; OffCoast, Inc., Hawaii.

3.2 Validation Data (WBS 3.2)

3.2.1 Multibody System Response Study (WBS 3.2.1)

3.2.1.1 Advancements

As discussed in Appendix C, Section 2.1, scale model tests of two MOB platform concepts, one developed by Brown & Root and one by McDermott Engineering, were completed under DARPA sponsorship at NSWCCD prior to this ONR S&T program. Test configurations included single and multiple modules connected by rigid and hinge connectors, respectively. The data collected includes motions, connector loads, and drift forces and moments. The objective of these tests was to identify general trends and magnitudes for typical MOB platform connector forces. For example, both test series discovered a torque sensitivity to relatively small near-beam waves.

The NSWCCD small scale models were intended to be essentially infinitely rigid. However, that was not the case, as evidenced by the fact that the measured rolls for the five McDermott modules were not equal. While the module elasticity was not large, it was sufficient to affect connector forces to an unknown degree. The elasticity was not measured, and that introduces some uncertainty into the use of this data for validation purposes. This study was initiated with full consideration of that uncertainty, but also recognition of its unique value as a multiple-module connected platform. The hope was that this subject evaluation of the data would yield qualitative conclusions with respect to connector loads.

The McDermott MOB platform was selected for analysis. It is comprised of five 1000 feet long by 400 feet wide modules for a total platform length of 5000 feet. This platform is hinge-connected at the deck level only. The 1:59 scale test was performed in the Maneuvering and Seakeeping (MASK) Basin at NSWCCD.

This task used the nonlinear finite element ABAQUS model with flexible modules and flexible connectors to model the global response of the five module platform and to assess the dynamic response characteristics of a MOB platform. Sample natural mode results are shown in Figure C-8. For the geometry, mass properties, and connectivity of this particular platform, the lowest resonance is seen to be a first torquing mode, with a period of around 7 seconds. The second mode is a combination of the sway and first bending modes, with a period around 6 seconds. Both periods are problematic since they are well within the range of significant wave energy. This illustrates how difficult the MOB platform design process can be, while also demonstrating the industry state-of-the-art at the inception of this Program.

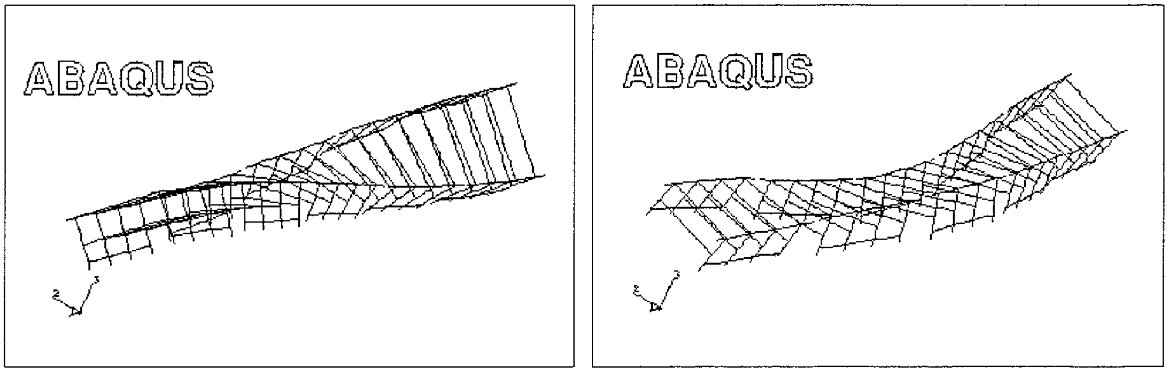

Figure C-8. Two longest period mode shapes from ABAQUS for DARPA-sponsored McDermott MOB Platform (not to scale).

The dynamic simulations to evaluate connector forces were more difficult because ABAQUS was not intended for offshore applications and does not incorporate industry-accepted algorithms for wave loading (i.e., Morison Equation). Because of that the numerical model used in ABAQUS was different than the physical model, and that introduced additional issues with interpretation of the results (specifically, the pontoons could not be modeled as horizontal members). The following general conclusions were made in the final report:

1. Results obtained from the computational model agree reasonably well with experimentally observed results for a majority of cases. This is especially true given the nature of the approximations made and the difficulty of reproducing wave tank conditions exactly. Sensitivity was observed in the wave tank tests which tends to lend further credibility to the computational model.

2. Torsion is a dominant natural mode of vibration for the MOB. This result ties neatly with the sensitivity that is seen when approaching beam sea.

3. Connector forces are dependent upon connector stiffness. This would indicate that connector structural stiffness should be carefully chosen to limit connector forces as part of the design process.

An indirect benefit of these general conclusions was that they served to reinforce the need for fundamental analyses for innovative offshore floating structures such as the longest MOB platforms.

3.2.1.2 Products

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3.2.1.3 Resource

University of Maine.

3.2.2 Hydroelastic Validation Data (WBS 3.2.2)

3.2.2.1 Advancements

No sufficiently accurate data sets were located at the inception of this Program which could be used to validate the hydroelastic models and the structural load interface software to be developed. For example, the data from the previous NSWCCD tests of the McDermott MOB concept (see WBS 3.2.1) are multi-body only.

As described in Appendix C, Section 1.2.2, the first step regarding this proposed test was to determine if any model scale test would return data with sufficiently accuracy and simplicity for validation purposes, and if yes, what test conditions were needed to insure that. A 2-day workshop was held in May 1998, and ended with two major conclusions: (1) the test was necessary, but (2) only if a series of recommendations were satisfied to assure data quality. The very large Maneuvering and Seakeeping (MASK) Basin at the Naval Surface Warfare Center Carderock Division (NSWCCD) was chosen for the tests. This facility is 360 feet long by 240 feet wide, which allowed for a 90-foot overall length of a 1:60 scale generic four-module MOB platform.

A very extensive series of preparations followed, including:

- Nominal semisubmersible and platform architectures were selected (number of columns, lengths, and connector properties).
- A preliminary full-scale design was completed to provide nominal mass and inertial properties.
- An independent design for the model semisubmersible module was iteratively completed such that the progression of the lowest natural eigen frequencies matched the full-scale values. Note that the elasticity of the model was purposely reduced to allow for measurable elastic deflections of the modules. An important and difficult part of the model design was the size and connection scheme used for the hydrodynamic components of the modules (i.e., foam on the pontoons) so that they did not interfere with the elasticity defined by the internal structural truss.
- A model scale 5-degree of freedom (DOF) multi-cantilever compliant connector was designed with a predetermined elastic stiffness.
- A comprehensive calibration was made of the spatial properties and repeatability of the waves in the MASK at different frequencies and incident directions.
- The semisubmersibles and connectors were built and extensively tested to confirm their mass, inertial, and [static] stiffness properties.
- A test uncertainty study was completed to maximize consistency and accuracy of all the data.

Figure C-9 shows a single module. A generic MOB platform geometry was selected consisting of an upper deck and four circular columns per side. The modules were very carefully designed and built to close tolerances. The overall dimensions of each test module was: 20 foot length, 8.33 foot beam, and a 2 foot draft, with a total weight of 5175 lbs. The columns were circular with a diameter of 1.667 feet. The pontoons were rectangular, 2.29 feet wide by 0.833 feet high, with elliptical end caps. The internal structural frame was made of ½-inch rigid polyvinyl chloride plate. The model structure was not a scaled version of the full-scale framing, but it did retain the same first three elastic modal responses (vertical bending, lateral bending, and torsion, respectively). It also was deliberately built so that the model would

exhibit larger elastic responses than any full-scale semisubmersible would, simply to enhance the value of this hydroelastic validation data. Medium-density closed-cell rigid foam was used to form the hydrodynamic shape, and the details of its attachment to the structural frame was one of the major issues in the model design. The foam was cut into 4-inch wide strips which were glued to the space frame; however, those strips were separated by ¼-inch soft foam spacers, which allowed them to flex along with the pontoon without adding additional stiffness or gaps that might induce unwanted damping due to squeezing effects; similar soft foam spacers were used to avoid interference between the column bottoms and pontoon flexure.

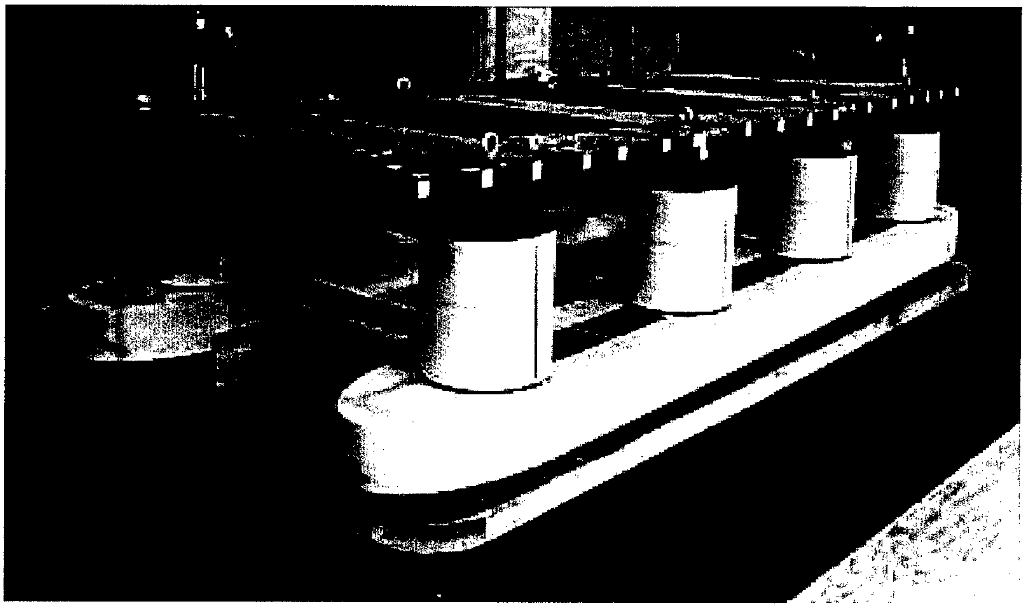

Figure C-9. Single module for MOB Hydroelastic Validation Test.

The connectors were also critical components for these tests, and received very careful attention in the design. The decision was made early on that the model scale connectors would not reproduce the characteristics of full-scale connectors, but would instead be deliberately softened so that the overall platform response would be clearly hydroelastic. Subsequently, the objective was to make them relatively stiff, sufficiently elastic to allow for non-negligible platform motions, yet robust enough to withstand damage. The final connector design is shown in Figure C-10 and an as-built connector in Figure C-11. The connectors were machined from high-strength aluminum. The design is based on orthogonal paired cantilevers, with load-sensing pins between them, such that forces and moments could be extracted. As shown in Figure C-9, the modules were connected with a pair of connectors that spanned the upper decks.

The longest/four-module MOB platform with connectors was approximately 90 feet long. This unprecedented length was longer than any other model ever tested at the MASK facility. NSWCCD had never had occasion to verify the spatial consistency of the waves generated in the MASK facility at this scale, so prior to the actual tests an extensive calibration was conducted to confirm the linearity,

repeatability, crest uniformity, long crestedness, and beach reflection characteristics of the short and long pneumatic wave generators at this scale. Fourteen probes were mounted in the tank to provide data. Results showed an average standard deviation of the wave amplitude along the crest of 10% of the mean value for all periods and wave energy. It was possible to reproduce irregular seas time histories with independent runs.

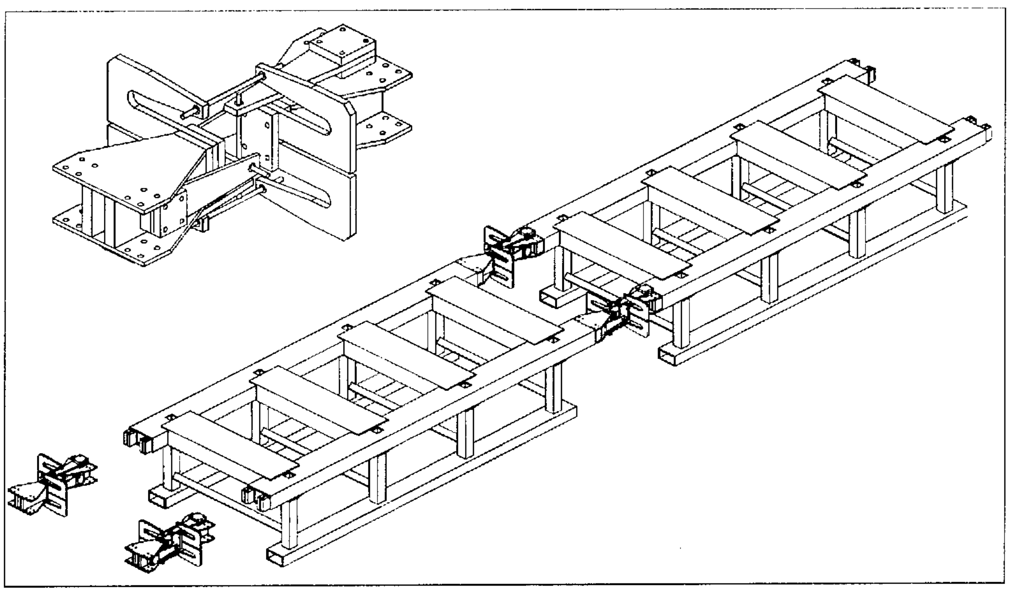

Figure C-10. MOB Hydroelastic Test Connector Design.

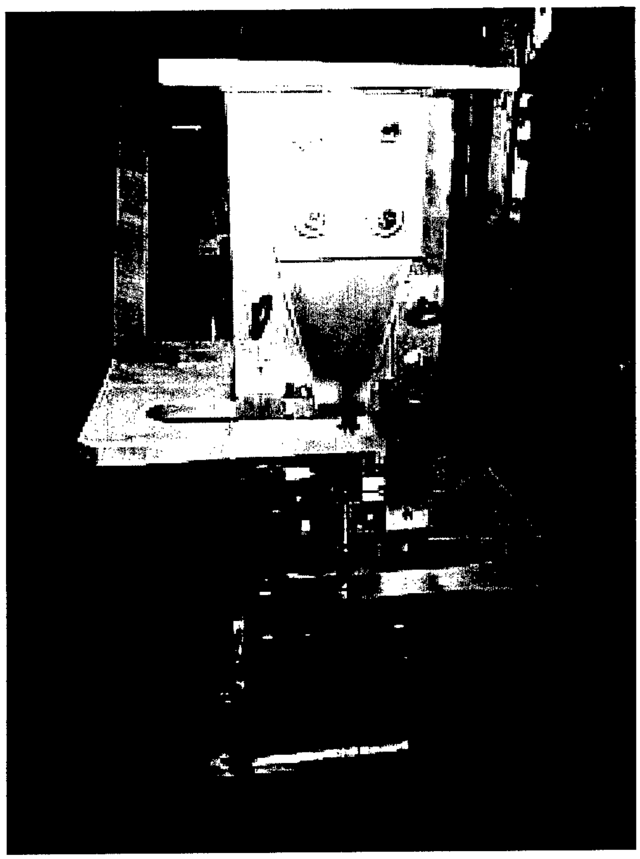

Figure C-11. As-Built MOB Hydroelastic Test Connector.

The tests were conducted from the fall of 1999 to the spring of 2000. One, two, and four semisubmersible modules with the compliant connectors were tested. Harmonic and random wave excitation was used for head, oblique, and beam incident directions. The measurements from this experiment included: 3-DOF motions at the top of each column, for a total of eight per module; these were used to determine module elasticity. Other measurements included 6 DOF motions above the center of gravity of each module, connector vector loads, hull stresses (120+ strain gages mounted throughout one module), mean drift forces and moments, and the wave field at a large number of stations near and far from the platform. The four module platform being tested in waves is shown in Figure C-12.

Figure C-12. Four module MOB hydroelastic platform in waves.

The planning, preparations, and conduct of this test were continuously reviewed by three of the attendees from the Hydroelastic Test Working Group (see Appendix C, Section 1.2.2). This provided quality control, and resulted in suggestions that significantly reduced the uncertainty in the data.

Project funding constraints precluded completion of the final test report. Also, no analysis of the data other than real-time sanity checks was performed.

3.2.2.2 Products

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7. Smith, T., MASK Basin 'B' Bank Wave Survey, NSWCCD-50-TR-1999\075, November 1999.

3.2.2.3 Resource

Naval Surface Warfare Center, Carderock Division (NSWCCD); Hydroelastic Validation Test Working Group.

3.2.3 Transit Draft Dynamics Model Tests (WBS 3.2.3)

3.2.3.1 Advancements

Designers of MOB semisubmersibles will certainly borrow extensively from industry experience. However, the larger size and military application associated with MOB introduces new design issues that needed to be addressed in this S&T Program. Military utility typically carries with it a time criticality factor, and that introduces two complications relevant here. The first is that a MOB module is expected to transit fully loaded with its logistics supplies (as opposed to industry practice which is to remove all possible topside weight for their transits). The second requirement is that it must transit to a new site regardless of the metocean conditions, which again is contrary to industry practice which is to either wait for the season with the mildest seas or to use a dry tow. When these MOB conditions are combined with the fact that the modules would be deballasted and riding with the waterplane near the top of the pontoons for minimum drag, the resulting scenario of a "top heavy" MOB semisubmersible transiting in moderate seas is unprecedented. The specific engineering concern here is that the high center of gravity and minimum waterplane area for buoyancy represents the most hydrodynamically unstable condition, which would be amplified by any rolling and pitching motions or encounters with large waves. Furthermore, the resulting large motions would induce to large accelerations for stored cargo, and in the extreme cause capsizing.

There was a technology shortfall for analyzing this behavior. Because of the changing waterplane this scenario cannot be modeled using traditional frequency domain diffraction theory models. The only applicable model was the time domain code LAMP which was described in Appendix C, Section 3.1.4, but even those results were suspect due to simplifications in the treatment of the free surface associated with that model. The selected approach was to conduct a series of model tests to bound and possibly better understand this design issue.

A generic1:75 scale MOB module (13-ft length) with eight columns was designed and built at the United States Naval Academy. Two sets of transit draft tests were successfully performed in their large seakeeping tank in December 1998 and April 1999, corresponding to zero and forward speed, respectively. Head, beam and oblique incident directions were used, for a variety of (harmonic) wave periods, and two drafts. Reports are in preparation. Figure C-13 illustrates the model responding to head waves.

Figure C-13. USNA semisubmersible at transit draft in head seas.

The dynamic response of a semisubmersible at transit draft involves known nonlinearities in the buoyant restoring force, but unknown nonlinear damping mechanisms. Therefore, before any mathematical models can be proposed and developed, the first requirement was to identify these damping mechanisms. The preferred form of answer was independent/coupled integro-differential equations for the global motion (as opposed to local-scale damping relationships consistent with element-level computational fluid dynamics or similar models). The technique chosen for this nonlinear system identification problem is called "Reverse MI/SO". This technique was recently developed via NFESC sponsorship, and is capable of efficiently identifying systems with unknown frequency dependent coefficients and unknown system nonlinearites. Reverse MI/SO is the only known technique capable of identifying and quantifying nonlinear integro-differential equation(s) of motion as required here. Initial analyses have been completed by the University of New Orleans, along with analyses using analytical nonlinear systems phase plane techniques developed there.

In addition, a limited study of this generic problem was completed before these tests using the LAMP time domain model. The objective of this study was to establish how applicable LAMP was to this problem, concentrating on the computational efficiency (convergence studies versus panelization for the body, free surface around the body, and inner/outer matching surface), and simplifications to the physics of the problem (neglecting dynamics of the water as it immersed/receded over the top of the pontoons). The study showed that LAMP could be applied to the MOB with varying waterplanes associated with transit draft dynamics. Convergence problems were encountered in some cases when LAMP failed to provide meaningful solutions; the reasons for this are not yet understood. The study also suggested that program efficiency still needed some improvement.

3.2.3.2 Products

1. Das, S., Transit Draft Roll Motion Stability of the Mobile Offshore Base Using Time-varying Coefficents, M.S. thesis, University of New Orleans School of Naval Architecture, December 2000.
2. Falzarano, J., J. Cheng, J., S. Das, W. Rodrigues, and R. Vassilev, MOB Tyransit Draft Transient Dynamics & Stability, 10th ISOPE Meeting, Seattle WA, May 28 – June 2, 2000.
3. Falzarano, J., W. Rodrigues, R. Vassilev, S. Das, and J. Cheng, MOB Transit Draft Dynamics & Stability, OMAE, New Orleans, LA, February 14-17, 2000.
4. Kriebel, D. and L. Wallendorf, Transit Tests on a MOB Module, U.S. Naval Academy Hydromechanics Laboratory, in preparation.
5. MCA Engineers, Analysis of MOB Module at Transit Depth Using LAMP, Costa Mesa CA, April, 1999.
6. Rodrigues, W., Transit Draft Roll Motion Stability of the Mobile Offshore Base Using Reverse MI/SO Techniques, M.S. thesis, University of New Orleans School of Naval Architecture, December 2000.

3.2.3.3 Resource

Testing: United States Naval Academy.

Analysis: University of New Orleans.

3.2.4 Air Gap Model Tests (WBS 3.2.4)

3.2.4.1 Advancements

The third of the three hydrodynamic validation tests addresses the air gap. For MOB semisubmersibles, air gap is defined as the net clearance between the free surface and the lowest point on the upper deck structure. Air gap is a difficult modeling challenge because it requires accurate simulation of the module motions as well as the incident, diffracted, and reflected wave fields under the module. The mathematical basis for state-of-the-art frequency domain models breaks down for moderate and larger waves, while time domain models are still developmental with unknown accuracy. These concerns are expected to increase for MOB applications due to addition of hydroelasticity in the motions of the connected platform. Note that accurate knowledge of the wave field is also critical because of its direct effect on vessels unloading or receiving cargo alongside.

A two-fold approach was chosen to (1) obtain experimental data and (2) perform a limited validation to estimate whether a modeling problem existed. As with all of the MOB validation experiments, a generic semisubmersible hull form was used. The tests were conduced at the United States Naval Academy, using the same generic 1:75 scale physical model used for the transit draft dynamics tests (described in Section 3.2.3) (except that operating draft was used for these tests). Several wave probes were attached to the model to measure the *relative* wave field/air gap, while others were fixed to the tank to measure the wave field with respect to an *absolute* axis system. Two categories of tests were performed. In the first category the model was fixed in position; this allowed for measurement of the radiative and incident wave fields. In the second category the model was allowed to move (subject to soft horizontal mooring lines to retain the general orientation of the model); this represented the full "air gap" phenomenon. Harmonic and random seas at head, oblique and beam incident wave directions were used in both categories.

Extensive supporting numerical studies were conducted using the time domain LAMP model; this model was described in Appendix C, Section 3.1.4. Comparisons were made of the measured and predicted wave field time histories at the known positions of the probes. The agreement for the radiative/incident wave field subject to the restrained model was excellent at all probes for all frequencies and headings. This confirmed the accuracy of that part of the LAMP hydrodynamic model. However, the air gap comparisons for the unrestrained model were rather poor. Consider the air gap associated with head seas and single period harmonic waves. The objective for each test was to come to a dynamic equilibrium, yielding a steady-state superposition of motions and wave components *all at the same frequency*. The test procedure used an initial linear ramping of the incident waves to minimize transient motions. The time domain LAMP model then naturally used that same ramping to initiate its simulation. Inspection of the results revealed that the ramping triggered various natural module frequency responses such as heave and pitch, and that the overall air gap showed a bichromatic (i.e., two sinusoids) response at the forced frequency, as was expected, but also at a separate natural frequency. Apparently, the assumption of inviscid fluid could not generate sufficient damping to decay the natural response to the initial ramping, and that resonant sinusoidal component then incorrectly dominated the remainder of the simulation. The comparisons for the head seas cases were not encouraging, so that the more difficult simulations for oblique seas were not attempted. No simulations were done with frequency domain models. The assumptions about the free surface in those models does introduce uncertainty regarding their use for air gap calculations when the wave amplitude is significant. However, by definition, those models only

allow for a response at the forcing frequency, which eliminates the problem exhibited here with the time domain approach.

3.2.4.2 Products

1. Kriebel, D. and L. Wallendorf, Air Gap Tests on a MOB Module, U.S. Naval Academy Hydromechanics Laboratory, in preparation.

2. Treakle, T., W.-M. Lin, K. Weems, S. Zhang, and M. Petzold, Air Gap Experimental Planning Support and Validation of LAMP Air Gap Computational Results of a Mobile Offshore Base (MOB), SAIC-00/1002, June 2000.

3.2.4.3 Resource

Testing: United States Naval Academy.

Analysis: SAIC Ship Technology Division.

4 RECOMMENDATIONS

The advancements in the Design Tools product area span from improvements in the hydrodynamic modeling to the collection of generic, laboratory-scale, hydroelastic and hydrodynamic validation data. The Design Tools category was arguably the single most important contributing factor for addressing the Program objective of estimating MOB feasibility. This statement is based on the recognition that landing conventional aircraft requires a connected MOB, which means the feasibility of MOB will to a large degree depend on the feasibility of the large and unprecedented connectors. And evaluating the feasibility of any connector design will require a reliable (read, accurate) estimate of the global connector loads. The many model advancements and experiments conducted under this product area were motivated primarily by this application.

The MOB Program has achieved significant advances that have elevated many modeling capabilities for offshore floating structures in general, and hydroelastic structures in particular. However, several important gaps remain that must be addressed before the design technology for a MOB can be regarded as complete. Specific examples include the following:

- Analyze and reduce the data collected in the NSWCCD hydroelastic validation test.
- Use the hydroelastic data to validate the newly advanced models.
- Exercise the many new computational models to identify their optimum usage and limits of applicability for:
  - The wave field affecting cargo transfer.
  - Air gap, particularly for energetic survival conditions.
  - Hydrodynamic-structural models interface.
  - Efficiency required for Level III fatigue studies.
  - Connector attributes (linear/nonlinear damping and stiffness).
- Further evaluate the time domain hydrodynamic programs and perform time-domain simulations of connecting/disconnecting operations.
- Estimate the mean and slowly-varying drift forces.
- Assess/advance viscous phenomena such as wake effects due to currents and/or MOB maneuvering, to determine the thrust required for dynamic-positioning systems.

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Alternative Concepts

1 OVERVIEW

The Defense Advanced Research Program Agency (DARPA) funded a few conceptual designs for a Mobile Offshore Base (MOB) under their Maritime Platform Technology program. The Office of Naval Research (ONR) assumed responsibility for these continuing design efforts in 1997.

Concepts for these early MOB designs were based mainly on the offshore industry's long experience with design, construction and operation of semisubmersible-type platforms. These traditional platforms are generally no larger than 100 meters (325 feet) in length and are used mostly for gas and oil exploratory drilling. In contrast, MOB was envisioned as a 1500-meter (5000-foot) long structure that would support conventional take off and landing aircraft (CTOL).

Participants of the ONR MOB Science and Technology (S&T) program immediately raised concerns about the applicability and adequacy of traditional methods for designing such a long structure to meet such a unique mission. They particularly questioned the chosen metocean design conditions, the simplistic structural responses and the high inter-module connector forces. In short, there was little consensus or analytical justification that these early designs were technically feasible. As designers re-evaluated their traditional design methods in response to the research concerns, their MOB concepts began to change.

As presently envisioned, a Mobile Offshore Base (MOB) is still a self-propelled, floating, logistics platform, consisting of one or more serially connected modules. The configuration of each MOB concept is now more structurally flexible, connector forces are smaller and global responses are less sensitive to severe metocean conditions.

Consistent with the S&T focus, the work in this product area was divided into two categories: System and Component Concepts. System concept development is necessary for identifying technology problems and supporting realistic cost estimating. Component development is important for resolving the critical technology problems, which including inter-module connectors and dynamic positioning (DP).

1.1 General Description

Unlike Navy ships, offshore platforms, and other traditional marine vessels or facilities, a MOB has military needs that dictate a type of floating structure that is both large and unique. Some of these mission needs, as listed in the draft 1995 Mission Needs Statement (MNS), are unprecedented compared to any floating structure ever built:

- Conventional take-off and landing of fixed-wing cargo aircraft at sea
- High-throughput cargo transfer to ships and landing craft in open oceans
- Large volume of climate-controlled storage for a variety of military cargo

- Occupancy by a very large group of military personnel even during storms
- Economical long-life maintenance and ease of repair
- Long-term station keeping in deep water sites anywhere in the world.

The goal of this Alternative Concepts product area was to improve the ability of the offshore industry to provide designs capable of satisfying the MNS. The specific S&T objectives were to identify technology gaps through competitive preliminary point designs and then to reduce technology "show-stoppers" through focused component developments. Consequently, this product area is divided into System and Component Concept categories.

Each of the major contractors, who developed the four MOB system concepts, initially approached their task with the opinion that they had all the engineering skills and tools to design and to analyze a MOB platform. The engineering skills included over 40 years of developing unique offshore platforms for petroleum and gas exploration and production. The engineering tools included design codes of practice and computer models, capable of computing the structural, hydrostatic stability and hydrodynamic response of many unique types of offshore platforms.

The process of developing conceptual MOB point designs helped our major contractors realize that their established engineering skills and tools were not necessarily adequate or efficient for properly designing, building, and estimating the cost of a unique offshore structure like a MOB. In fact, each contractor identified several technology gaps in both their engineering skills and in the overall design process.

The following uncertainties and deficiencies in industrial capabilities, that affect MOB concept development, existed prior to the MOB ONR program:

- ***Metocean loads:*** The size and operational demands of a MOB are unique. Available analysis tools and metocean data to establish structural response were insufficient or inadequate for such a long structure like MOB.
- ***Suitable concepts:*** No platform concepts existed that would fulfill the MOB requirements with respect to aircraft operation in specified sea states, survival during extreme conditions, transit speed, stability in damage condition etc.
- ***Mooring, anchoring and positioning systems:*** No types of stationkeeping (mooring anchoring and dynamic positioning) systems were available with the capacity necessary for a MOB.
- ***Constructability and construction schedule:*** What facility and dock requirements does MOB need for construction; do such facilities exists today, and can they be reasonably scheduled?
- ***Connectors:*** The inter-module MOB connector exceeds today's experience in both size and force transfer capacity.
- ***Fatigue:*** The MOB has a service life requirement of 40 years without docking for maintenance. How to insure the required fatigue strength was considered a critical issue.
- ***Durability, maintenance and repair without docking:*** The "no docking" criteria required investigation into structural materials with a record of low maintenance and a long service life. Credible procedures for repair while at sea needed to be investigated.
- ***Cost:*** A methodology and strong basis was missing for developing life cycle costs and overall project schedule estimates for a MOB.

1.2 Quality Assurance

To assure quality for all deliverables in this product area, each deliverable was reviewed in draft form by several independent reviewers. These reviewers included the American Bureau of Shipping (ABS), Max Cheung and Associates, the Naval Facilities Engineering Service Center (NFESC) and other MOB participants, as appropriate to find the right level of expertise. The product leader for this Product Area gathered the comments from each reviewer, checked each comment for appropriateness, and drafted an official list of government comments.

The official government comments were generally organized into two sections: those general to the entire deliverable, and those addressing specific items in the deliverable. Government comments were meant simply as information to improve the content of the report and in no way were intended to direct the contractor. Each contractor chose how and how many of these government comments to incorporated into the final draft of each deliverable.

Semiannual MOB Technology Conferences were held every six months to give all participants a chance to exchange information and see what others are doing in the other product areas. This exchange was most valuable to the concept product area, because it gave designers and researchers a neutral forum for communicating, sharing ideas and appreciating what each group had to offer the overall MOB program. The conference gave designers a chance to communicate their unmet needs to the researchers, and gave researchers valuable feedback on what works and what does not work in the real world.

In addition, focused working groups were formed to provide more formal inter-communication. These working groups included key participants irrespective of which product area in which they were working. Two working groups were formed in this product area. The first focused on connectors and the other focused on dynamic positioning.

1.2.1 Connector Working Group

The program allowed each contractor, who was developing a MOB system concept, to develop an inter-module connector suited to their system concept. Because of common requirements for all connectors, it was useful to collaborate on connector technology.

As such, a Connector Working Group met every three months to assess the overall feasibility linking very large ocean platforms for MOB application. The group discussed options for designing, building, and repairing MOB inter-module connectors. The group gave specific direction to the various design and research efforts that were actively going on in connector technology.

Brown & Root (WBS 4.2.1) had a contract to survey the industry and then draft a specification document for MOB connectors that cited such criteria as reliability and maintainability, including the mechanics of repairing or replacing a failed connector. An agreed purpose of the this working group was to assist Brown & Root in that study. Official members of the Connector Working Group are listed below. At each meeting, many interested non-members also attended.

Name	Organization
Billie Karrh	Chairman, Naval Facilities Engineering Service Center
Richard Brown	Atlantic Research Corp. SEQUA
Petter Bjerkseth	Kvaerner Maritime a.s.

Dr. Liyong Chen	J. Ray McDermott Engineering
James Haney	J. Ray McDermott Engineering
J.L. (Joe) Korenek	Brown & Root Energy Services
Richard Lewis	Naval Surface Warfare Center – Carderock Division
Richard Lundberg	Bechtel National, Inc.
Dr. Richard Messier	University of Maine
Clyde Nolan	Brown & Root Energy Services
Dr. Joe Penzien	International Civil Engineering Consultants, Inc.
Eric Pettersen	Kvaerner Maritime a.s.
Dr. Ron Riggs	University of Hawaii
Gunnar Rognaas	Aker Maritime a.s.
Stephen Slaughter	MCA Engineers, Inc.
Richard Yee	ABS Americas
Dr. Robert Zueck	Product Area Leader, Naval Facilities Engineering Service Center

Dr. Joe Penzien, a recognized researcher in related structural components, was the main ONR advisor to the working group. After six meetings, the group drew several formal conclusions including the following:

- One cannot separate the design of the connector from the design of the overall MOB. Because of structural compliance, the two are inter-dependent. As such, one must first chose a MOB system concept before writing a connector specification.
- The forces acting on a connector are not easily determined and conservative estimates of these forces lead rapidly to connector concepts that are too large to build.
- Size limits for MOB connectors are determined mostly by manufacturing limits. These include how thick one can roll plate steel and how large a unit of rubber one can vulcanize.
- Due to mechanical wear, MOB connectors would most likely need to be changed out or otherwise overhauled several times during the desired 40-year life of a MOB.
- It was generally agreed that once realistic requirements could be found for MOB connectors, the industry possessed enough ingenuity to be able to design, build and repair them.

1.2.2 Dynamic Positioning Advisory Group

Dynamic positioning is a critical component for all MOB system concepts. The challenge here was to dynamically position MOB modules in close relative proximity to one another. An independent advisory board of senior experts from the offshore drilling industry was organized to gather opinions about the state-of-art in dynamic positioning technology.

Name	Organization
Howard Shatto	Chairman, Independent Consultant
Pete Fougere	Transocean
Dillard Hammett	ENSCO
Frank Williford	ENSCO
Dr. Max Morgan	Aspen Technology
Charles Sims	Global Marine

Extrapolating from 40-years of current DP experience, the panel concluded that dynamically positioning a MOB was technically feasible but recommended further research in the subject, including the following:

- Evaluate the candidate control strategies
- Further investigate slowly varying wave drift forces
- Focus on the difference in environmental forces and the spatial variation versus module separation
- Improve upon the present 5-year-to-failure reliability
- Define a robust means to disengage modules when failure occurs.

Subsequent joint-industry proposals by the industry have in fact called for even more research into drift forces and advanced control theories. The MOB program office chose to focus on evaluating control strategies and generating physical performance data from a multi-module dynamic positioning experiment because they would directly improve reliability and show the path to a graceful means of assembling and disassembling MOB modules.

2 TECHNICAL ADVANCES

2.1 Key Issues

The preliminary MNS has not been approved, and thus firm operational requirements do not exist. As a result, each contractor interpreted the broad statements of intent in the preliminary MNS somewhat differently and postulated candidate concepts for MOB that they felt best matched the mission needs. The following nominal list of engineering requirements derived from the MNS and related technical issues apply:

Physical Size: The overall length of the MOB would have to be at least 1500m (5000 ft) long and 122m (400 ft) wide to accommodate conventional landing and take-off of the McDonnell Douglas C-17 cargo aircraft. As such, the MOB would be larger than any floating vessel ever built, thus raising the obvious technical issue of structural integrity. Removing the requirement for C-17 (but still C-130) flight operations essentially halves the MOB length.

Structural Modularity: Depending on temporal needs, the MOB may operate as a single module, capable of transferring cargo by helicopter or ocean vessel, or as a connected series of modules that are capable of

transferring cargo by fixed wing aircraft. Modularity raises the issue how one connects these large modules at sea.

Logistics Capability: The MOB should have up to 800,000 m^2 (9 million ft^2) of environmentally controlled dry cargo storage and up to 40,000 m^3 (10 million gallons) of fuel storage. These large volumes require innovative methods for getting timely access to all the cargo for selective retrieval and refurbishment thereof.

Operability: House up to 3,000 troops, support aircraft operations in winds up to the normal limits of a C-17's ability to land or takeoff, and transfer cargo to and from ocean vessels in seas exceeding the normal loading limits of most military cargo vessels.

Survivability: The MOB must survive in the most severe of environmental conditions, including hurricanes and typhoons. Given a lack of experience with large floating structures like a MOB, it is necessary to investigate its failure modes and methods to avoid them.

Maintainability: To minimize total life cycle cost, forty years is the desired design life between major overhauls of the MOB. Innovative fatigue design, at-sea repair, and component details become major technical issues for such a long design life.

Station Keeping and Mobility: Depending on changing mission needs over the life of a MOB, the separable modules may be stationed individually for different duties in various deep-water locations. To be brought rapidly together for fixed wing aircraft operations, the modules must transit at high speed.

It is important to recognize that these requirements are subject to change with related changes in mission needs. Therefore, the alternative concepts being investigated in the ONR MOB program may not be the preferred concepts if and when a MOB is built.

The ONR program divided the S&T thrust for Alternative Concepts conveniently into two major categories:

- Systems
- Components.

2.1.1 System Concepts

The concept of a large, floating, offshore structure, which could be utilized in much the same way as a military land base, has been considered at various times and for various specific purposes since the early 1900s. A few system platform concepts were developed specifically for use as a MOB under previous U.S. Government funding. These concepts and the contractors who worked on them were:

- Very Large Mobile Offshore Base (VLMOB): Seaworthy Systems, Inc.
- Ultra-Large Monohull Offshore Base (ULMOB): Band, Lavis & Associates, Inc.
- Rigidly Connected Semisubmersible Modules: Brown and Root, Inc.

The VLMOB is based on converting a very large crude oil carrier. About 335m (1100 ft) long, this single hull ship would be capable of operating as a multi-purpose mobile offshore logistics base, but would not be long enough to provide fixed wing aircraft operations.

The ULMOB is based on monohull modules, each about 505m (1660 ft) long. By rigidly connecting modules end-to-end, long runways can be created. Although initial estimates show very large loads and

resulting motions, the results were generally inconclusive.

The Rigidly Connected Semisubmersible Modules concept consists of up to six semisubmersible steel modules, each 180m (600 ft) long, connected rigidly. The rigid connectors effectively create one long semisubmersible hull, resulting in very large connector forces, which exceed reasonable design limits.

These prior concept studies generally focused on rigid monolithic hulls or a series of modules that were structurally integrated to provide an essentially continuous rigid platform. A review of these prior concept studies indicate that there were major structural issues associated with the response of structurally continuous concepts under extreme wave-load conditions that might not be overcome.

A monolithic, full-length, full-depth hull would have very large structural stresses along the keel due to simple hog and sag deflections. Allowing the structure to flex with the shape of the sea surface can reduce these stresses. One can develop this structural compliance by dividing the hull into modules that are allowed to move relative to each other. Although this compliance to the sea surface reduces the overall structural stresses by attracting fewer loads than a monolithic rigid structure, the relative motion between modules results in a flight deck that may not be straight or continuous. Acceptable system platform concepts are those that seek an optimal level of structural compliance, in other words, a balance between structural stresses and inter-module motion.

The ONR MOB program looked at modularly compliant platform concepts as an alternative to these structurally continuous concepts. We chose to avoid a long rigid monohull and instead concentrate on concepts that subdivide the long MOB into modules that can be individually configured for independent operation or flex while assembled to minimize the dynamic loads.

Assuming a fixed set of notional mission requirements for MOB, the ONR program pursued development and evaluation of four alternative MOB concepts. Each concept deals uniquely with the issue of compliance. The main difference among the four system platform concepts is principally the method used for connecting the semisubmersible modules to form the assembled MOB platform of sufficient length to land conventional fixed-wing aircraft.

The semisubmersible hull was originally developed as a very low-motion drilling platform for the offshore oil and gas industry. Figure D-1 shows a typical semisubmersible hull module for MOB. The module consists of a box type deck supported by multiple tubular columns, connected at their base by two parallel pontoons.

Figure D-1. Typical Semisubmersible Modules (unconnected).

Rolling stock and other dry cargo are stored on the two lower decks of the deck structure while liquids are stored in the pontoons and columns. This arrangement eliminates most voids below the water surface, thus minimizing greatly the danger of damage due to flooding. The hull construction is conventional stiffened steel plate as seen in ships and semisubmersible drilling units.

When on site, the unit is ballasted down so that the pontoons are submerged below the surface wave zone. This creates a minimum exposed surface to horizontal metocean forces and generates a small water plane area, removing sensitivity to large waves. In waves, where ships may be rolling more than 10 degrees, a comparable semisubmersible hull will often roll less than 1 degree. This inherent low motion (stable) characteristic gives the semisubmersible hull its greatest advantage over conventional ship hulls.

When transiting between operational sites, the unit is deballasted and floats with the pontoons on the surface, and consequently travels on the surface much like a catamaran. This reduces form drag, allowing transit speeds approaching that for conventional cargo ships.

The semisubmersible hull form provided a good basis for the MOB requirements of both on-site stability and the need for rapid transit. By developing several candidate MOB system concepts, this product area provided the following important benefits to the overall MOB program:

- Assessment of the completeness of engineering requirements.
- Identification of those parts of the classification processes that needed modification or extension.
- Characterization of deficiencies in analysis tools, data, and hardware designs.
- Identification of technology gaps for designing, building, and operating a MOB.

2.1.2 Component Concepts

During the development of the MOB alternative system concepts, certain high-risk technology gaps emerged that were common to all or many of the MOB system concepts. Rather than have each system development contractor attempt to tackle each of these common technology gaps, we choose to focus one or more contractors on any given critical technology gap. This strategy of collaborative investigation of a common technology gap was useful in maximizing the benefit of limited research funding for all MOB participants.

These technology gaps included the following:

- Inter-Module Connection
- Multi-Module Dynamic Positioning
- Pneumatic Stabilization
- Stationkeeping/anchoring
- Lightweight Decking
- Open Sea Cargo Transfer.

2.2 Major Products

The main products generated in this Alternative Concepts product area are new MOB system concepts (and in some cases preliminary designs) and component concepts. Each conceptual MOB system design is described in a series of documents on topics such as design basis, specifications, drawings, engineering calculations, cargo layout, hydrostatic stability, computer analysis, and proof of concept reports. Similarly, the work associated with each component concept is documented in reports specific to the nature of each type of component.

2.2.1 Systems (WBS 4.1)

WBS	Task	Description
4.1.1	Hinged Modules: Five semisubmersible steel modules connected by compliant hinges	Designed, analyzed and tested a connected MOB concept that relieves large structural stress by allowing discrete movement between modules
4.1.2	Flexibly Bridged Modules: Three semisubmersible steel modules connected by flexible steel truss bridges	Designed and analyzed a connected MOB concept that relieves large structural stress through continuous physical flexibility and damping between modules
4.1.3	Independent Modules: Three semisubmersible steel modules positioned dynamically relative to one another	Designed and analyzed an unconnected MOB concept that relieves large structural stress by eliminating physical connectors
4.1.4	Concrete/Steel Modules: Four semisubmersible modules with steel deck and concrete hull	Designed and analyzed a hybrid concrete/steel MOB concept to evaluate alternative material choices
4.1.5	Develop procedure for basic evaluation of technical feasibility of the entire breadth of concepts.	Expanded the range of feasible alternative system concepts given specific changes in MOB mission

2.2.2 Components (WBS 4.2)

WBS	Task	Description
4.2.1	Inter-Module Connector Technology	Evaluated a family of concepts for structurally inter-connecting MOB modules
4.2.2	Elastomeric Connector Material	Developed, analyzed and tested unique elastomeric material (graphite-fiber-reinforced, urethane-matrix) for use in inter-module connectors
4.2.3	Compliant Connector	Developed, analyzed and tested several innovative concepts for a hinge-type compliant connectors to reduce inter-module forces
4.2.4	Multiple-Module Dynamic Positioning System	Characterized unique hardware for reliable dynamic positioning of MOB modules
4.2.5	Control Strategy for Dynamic Positioning	Developed and physically tested new nonlinear control strategies for stable and efficient dynamic positioning of MOB modules relative to one another
4.2.6	Pneumatically Stabilized Platform	Analyzed and tested a novel concept for mitigating local dynamic platform motions via air movement between buoyancy chambers, whose bottoms are open to the ocean water
4.2.7	Suction-Pile Anchors	Developed and tested a holistic design capability to anchor MOB and its individual modules
4.2.8	Lightweight Decking	Designed, manufactured and tested a new type of composite (fiberglass) panes as alternative decking material.
4.2.9	Open-Sea Cargo Transfer	Investigated wave environment and small vessel motion alongside a MOB. Developed concepts for improving the local wave environment.

Each of these studies is described in the next Section.

3 PRODUCTS DESCRIPTION

3.1 Systems (WBS 4.1)

The primary objective of each effort in this System Concept product area was to design a MOB platform concept that met the 1995 draft Mission Need Statement (MNS) for a MOB. The MNS contained only basic storage capacities and marine and operational needs for a MOB. From their own interpretation of the MNS, each contractor developed their own set of baseline requirements and engineering design criteria. These requirements and criteria were essential for establishing adequate physical dimensions for the airfield, the seaport, and the pre-positioned storage facilities.

Each contractor followed a similar concept development procedure. They first established design requirements and objectives for a baseline MOB configuration, outlined functional specifications and identified relevant design codes and standards. They used the following guiding principles to develop the baseline configuration:

- Proven offshore technology shall be used to the largest possible extent.
- Connecting strictly rigid MOB modules will result in connector forces of a magnitude that are beyond current industrial technology. By introducing flexible elements and elements with damping characteristics, the large connector forces can be significantly reduced.
- Deck layouts should have the maximum amount of open space possible to best support cargo storage and handling functions.

Being driven by the minimum runway length necessary for operating fixed-wing cargo aircraft, particularly the Boeing C-17 Globemaster, the overall physical dimensions of each system concept are similar. However, within these basic dimensions, the internal cargo spaces and structural approaches to each concept are different.

For system conceptual design, it was assumed that the MOB would strictly be a logistics platform with no direct war-fighting mission. As such, it would remain in the theater of conflict but well out of direct military threat. Consequently, consideration of military threats and space for sophisticated weapon systems was not part of any conceptual design effort.

As active competitive members of the offshore facilities design and construction community, each contractor was allowed tremendous latitude in their choice of how to approach the technical difficulties associated with such a uniquely large marine structure. The main difference among the four system platform concepts is principally the method used for connecting the modules to form the assembled MOB platform of sufficient length to land conventional fixed-wing aircraft:

- Hinged Semisubmersible Modules
- Semisubmersible Modules with Flexible Bridges
- Independent Semisubmersible Modules
- Concrete/Steel Semisubmersible Modules.

Given this choice of MOB concepts, it is natural to ask, *"Which concepts are technically feasible?"* All four MOB system concepts were found to be feasible. Each has its strengths and weakness, all of which appear to be solvable with proper engineering design principles and additional research.

Given four technically feasible concepts, it is then natural to ask, *"Which one is best?"* Since the U.S. Department of Defense has not yet formally approved the requirements for a MOB, it is inappropriate to recommend any particular concept at this time. This question is best reserved for the acquisition stage, when presumably, the true mission needs of a MOB platform can be clearly detailed and approved by the cognizant organization within the military which will own and operate the MOB.

Each of the four system concepts advanced by MOB are described next.

3.1.1 Hinged Modules (WBS 4.1.1)

3.1.1.1 Resource

McDermott Technology, Inc., in Virginia was the main contractor. McDermott Shipbuilding, Inc. (MSI) in Louisiana performed the majority of the work, with major involvement from McDermott Engineering Houston LLC (MEH), now called J. Ray McDermott, in Texas. Under subcontract, Seaworthy Systems developed cargo interface systems, and the University of Hawaii provided analytical modeling results. Also under subcontract, the Naval Surface Warfare Center, Carderock Division (ex-David Taylor Model Basin) conducted a scale model experiment for this particular concept. This effort was originally part of the DARPA Maritime Platform Technology program that preceded this ONR study.

3.1.1.2 Advancements

Hinged MOB Concept. Simply referred to as the Hinged MOB, the results of this design actually represent all MOB platforms with "discrete" connectors. This system concept consists of up to five rectangular semisubmersible steel modules, each 300m (985 ft) long (Figure D-2). Hinge type connectors that allow for relative motion in pitch between adjacent modules link the modules. McDermott developed two types of discrete connectors: a "piano" hinge and a nonlinear compliant connector.

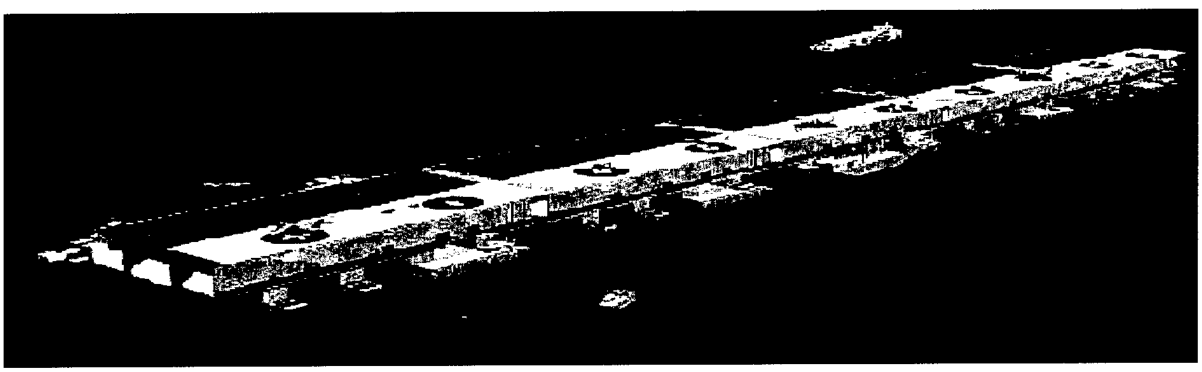

Figure D-2. Hinged Semisubmersible Modules.

A dynamic positioning system provides absolute positioning of the overall MOB during operation and relative positioning of each module during connection. The work on this concept is fairly complete to the preliminary design level. It includes fairly detailed structural design calculations and analysis of the hull and the deck and preliminary hull mechanical outfitting. The work also includes a detailed layout of all internal spaces for cargo, showing access routes, cargo transfer methods and personnel accommodations. McDermott prepared detailed weight and cost estimates for its MOB concept.

Hydrodynamic and structural analyses indicate that connector forces for the "piano hinge" become excessive in oblique waves due to twisting (torquing) along the length of MOB. As a result, the "piano hinge" connector was dropped in favor of a "compliant connector."

Compliant Connector. McDermott's nonlinear compliant connector utilizes an arrangement of pinned and elastic (rubber cone) connections that provide concentrated flexibility in the three rotational degrees

of freedom between modules. This concept is more fully described in Section 4.2.3, WBS 4.2.3. Ideally at low force levels, the cones are stiff and provide for a straight runway. At high force levels, the cones collapse and provide reduced stiffness, thus allowing compliant motion and reduced stresses. This connector is also designed with regard to quick connection and disconnection of the modules in a dynamic sea environment.

The non-linear compliant connector is the key to McDermott's connectable modules concept. They permit the assembled structure to connect in seas up to Sea State 5 and remain connected in 100-year storm conditions without limits on orientation or powering. The connectors in these conditions, making it possible to handle C-17 cargo aircraft (5 or 6 modules) and even commercial aircraft (8 modules) on a MOB platform. The design also permits disconnecting the modules without damage to the connectors or other structure in up to Sea State 7 so that a commanding officer has the flexibility to weather storms in either a connected or disconnected state.

Hydrodynamic and structural analyses demonstrated that rigid-body assumptions of the hull are not valid for MOB and that a time-domain approach is necessary when nonlinear compliant connectors are specified. However, because time-domain approaches are not traditionally used for analysis of floating structures, validation against experimental data is necessary.

Experimental Results. Tank tests verified that the force predictions of existing hydrodynamic codes (WAMIT and MOSES) were only partially adequate for linear inter-module connections. Extensions of these codes to non-linear connector devices adds even greater uncertainty.

During these same tank tests, modifications to the column/lower hull geometry eliminated an observed problem of wave run-up on the columns slapping on the bottom of the upper hull. Lower hulls should be ship-shaped to maximize the deployment speed (15 knots in our design).

Build Strategy. The shipbuilding and offshore marine construction infrastructure of the United States can build the semisubmersible modules using a combination of the modular construction and offshore assembly techniques pioneered by McDermott and currently widely used in the offshore construction industry. The concept is to fabricate major components in existing facilities on all three coasts of the US and assemble them using an offshore construction slip in the Gulf of Mexico and deepwater sites nearby.

A component-based build strategy will spread the economic impact of such a large steel fabrication activity like MOB over a larger geographic area. Studies showed that this strategy could build the first MOB module in 30 months with subsequent completions at 12-month intervals.

Cargo Handling. Because of the need to maintain clear air to the sides of the flight deck for flight safety, conventional pedestal cranes are not possible for ship cargo/container loading and unloading. McDermott used the rail type RoboCrane conceived by the National Institute for Standards and Technology (NIST) as the basis for its sea-based cargo transfer systems. Based on simulations, it is believed that one can achieve near dockside rates of transfer for large commercial container ships up through Sea State 3, with small degradations in Sea State 4.

A specially-designed RO/RO transfer platform and ramp located on one side of each module will permit RO/RO transfers at dock-side rates up to Sea State 3 for commercial RO/RO vessels. The movement of the auxiliary ship, not the MOB, its cargo handling systems or its ramps, will limit transfer to small vessels.

Issues Remaining to be Resolved. Major areas requiring continued technology funding include:

- validation testing in a model basin to benchmark hydroelastic effects, non-linear connector predictions, and connection/disconnection operations
- developing and testing high performance computer-controlled cargo handling equipment
- investigating alternative motion mitigation schemes to improve cargo transfer to smaller vessels
- developing full-width bridges between connected modules
- performing bench-scale and semi-scale testing of compliant connector systems
- verifying operation and reliability of multi-body dynamic positioning systems

3.1.1.3 Products

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3.1.2 Flexibly Bridged Modules (WBS 4.1.2)

3.1.2.1 Resource

Kvaerner Maritime a.s. (now called Moss Maritime, a.s.) in Norway and the Boeing Company in Washington formed a joint venture, SeaBase, Inc., in New York, to develop a SeaBase concept for the U.S. Navy. In a similar joint venture with Boeing and two Russian companies, Kvaerner has developed an offshore semisubmersible platform for launching satellites called SeaLaunch; many technological parallels exist between MOB and SeaLaunch.

3.1.2.2 Advancements

SeaBase Concept. Simply referred to as SeaBase, this system concept consists of three semisubmersible steel modules, each about 235m (770 ft) long connected by two very long and flexible floating truss bridges, each about 410m (1350 ft) long (Figure D-3). Each flexible bridge is connected to adjacent semisubmersible modules using the weight of the bridge resting upon a keyed connection. Pneumatic bumpers are used to absorb vertical relative motion, and vertical bumpers are used to absorb relative surge and sway energy during the docking maneuver. The flexible bridges help maintain a continuous flight deck while still providing the desired compliance to accommodate relative motions between the rigid semisubmersibles.

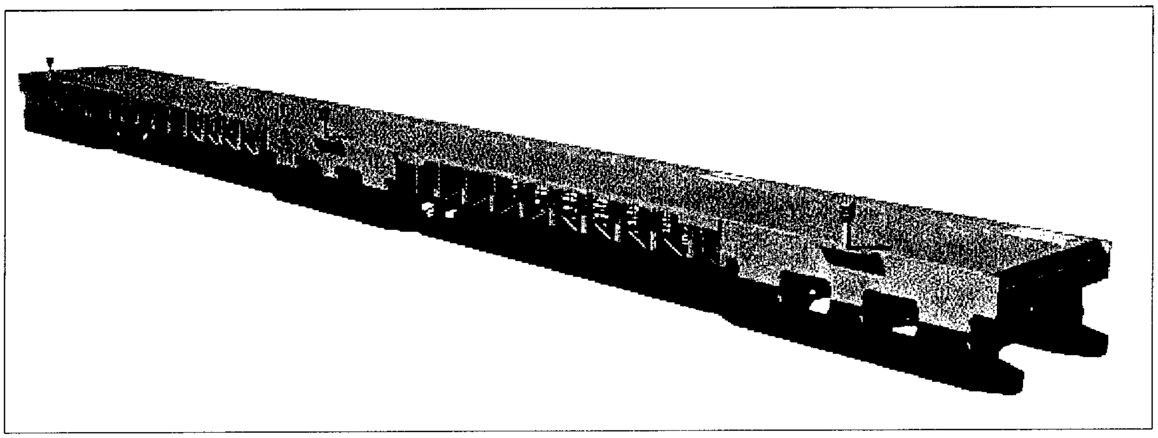

Figure D-3. SeaBase (Flexibly bridged modules) Concept.

The Main Module decks were purpose designed for storage and handling of all types of dry cargo, military vehicles and equipment, ordnance, ship harbor and dock and well deck functions. Large areas were also dedicated for machinery spaces and accommodation of permanent and transient personnel. Volumes in the main module hull were designed for storage of all types of liquid cargo, such as aviation fuel, marine fuel, and fresh water.

Each Flexible Bridge was designed as a minimal structure with no cargo storage capability, but must nonetheless have enough buoyancy capacity to float into position prior to connection. A dynamic positioning system on board each module/bridge provides absolute positioning of the overall MOB and relative positioning of each module during connection.

By being modular, SeaBase is capable of adjusting its length to enable maximum adaptability in operation. It allows for operation as independent MOB units (Main Modules), as a fully configured MOB (three Main Modules and two Flexible Bridges) or as intermediate size MOB (two Main Modules and one Flexible Bridge). The length of the complex may even be increased by further expansion to four Main Modules and three Flexible Bridges. Each module is equipped with dynamic positioning plants capable of keeping the complex or individual units in position as well as providing propulsion for transit purposes.

The long length and inherent flexibility of the Flexible Bridges allows the semisubmersible modules to move relative to one another without the stress concentrations found in a "discrete" connector. To accommodate unique technological challenges, Kvaerner modified the conceptual design of its SeaBase from its original concept. These changes included larger diameter columns on the Main Modules to improve dynamic response and bigger pontoons on the Flexible Bridges to achieve greater transit speed.

Kvaerner provided detailed weight, cost and schedule estimates that reflect their experience with international shipbuilding and offshore yards. Their figures are based on a very general level of input and should be looked upon as what they are, namely estimates only. The output however, forms a sound basis for the further planning of the MOB project.

Flexible Bridge and Connection to Main Modules. The key advantage to the Kvaerner concept is that the flight deck connection is fixed. There is no relative motion at the flight deck, hence, there is no need for an articulated bridge. The deformations are distributed over the entire length of the bridge, thus avoiding the usual stress concentrations typical of "discrete" connectors like hinges.

By providing "distributed compliance" in the overall MOB structure, the Flexible Bridge maintains a runway that is continuous in both translation, rotation, and equally importantly, runway slope. This type of continuous runway is ideal for all air operations including take-off and landing of large, conventional fixed-wing aircraft and tactical aircraft.

With the flexible bridge, it is conceivable to allow the SeaBase to remain connected under even the most extreme of metocean conditions. This ability to not have to disconnect in extreme weather (and later reconnect) would offer a distinct operational advantage in relation to military strategy and operations.

Due to its large compliance, the Flexible Bridge inherently has natural modes of dynamic motion that are easily excited by waves. This dynamic sensitivity requires structural dampers on the Flexible Bridge to control structural resonances and thereby limit fatigue. The connectors between the Flexible Bridge and the Main Modules are simple teeth-like elements as shown in Figure D-4. With such simplicity, the connection/disconnection operation is also simple since no complex moving parts are required.

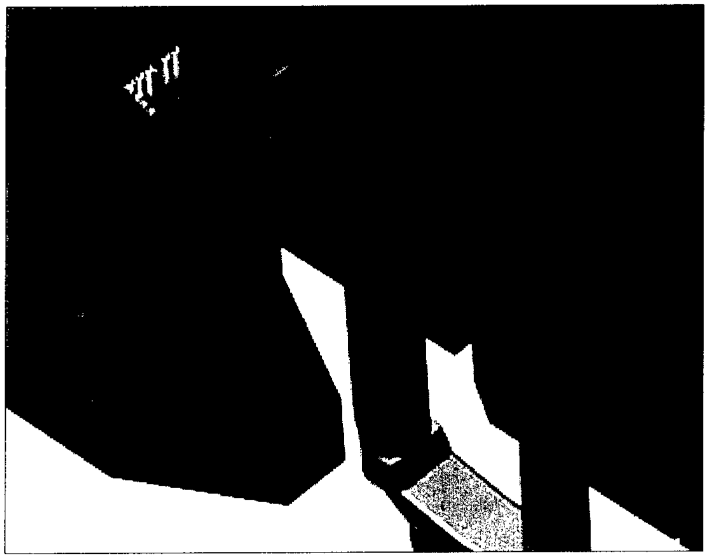

Figure D-4. Connection between Main Module on Right and Flexible Bridge on Left.

Current data indicates that the resultant forces and stress levels (fatigue and dynamic response) of this approach are moderate enough to allow SeaBase to remain connected in a Sea State 8 storm. Surviving such a storm, with a significant wave height of 14 meters (46 feet), is possible to the unique flexibility of the SeaBase.

Preliminary studies indicate that the SeaBase can safely perform the connection and disconnection operations in Sea State 5 and 7 environmental conditions having significant wave heights of 5 and 7 meters (16 feet and 23 feet), respectively.

MOB Airfield Design Requirements. Airfield Operations and Cargo Handling Operations have been analyzed to document the operational feasibility of the SeaBase concept. The basis for the SeaBase airfield concept has been derived as much as possible from standards used for land based airfields. The field is generally divided into two functional areas: main runway and aircraft parking.

A series of control towers would be located along one side of the airfield. They would be functionally allocated to air traffic control and ground control. During the initial development of the airfield layout, assumptions were tested and reevaluated to each mission. The overall conclusion from the airfield requirement study is that the SeaBase airfield layout can successfully support each of the missions defined, given an appropriately safe runway length.

Issues Remaining to be Resolved. Several technological aspects must be resolved to eliminate remaining uncertainties specific to a long and highly flexible structure like the SeaBase concept:

- Given the flexibility of the bridges, accumulated energy and decreased fatigue life of the structural elements that make up the flexible bridge has not been adequately explored.

- The concept may still require disconnection of the modules to survive in high storm conditions. As such, several critical items about the connection and disconnection operation are still unknown such as the length of time needed for connection/disconnection, the sea states in which these operations can be done, and the dynamic positioning capabilities needed.
- The weight of the flexible bridge resting upon the semisubmersible modules raises the issue of how to achieve a fail-safe release of this inter-module connector in the event that some of the ballasting features of the bridge and/or module become disabled.
- Given recent research efforts in improving the state of practice in crane automation and motion compensation, it would be beneficial to determine how these advanced cargo handling methods improve SeaBase deck layouts and overall cargo management philosophy.
- The spatial nature of ocean waves including topics like wave coherence, wave crest length, solitons and rogue waves is rather misunderstood and cannot be easily applied to MOB design. We need better understanding of the mechanisms driving these wave phenomena because of their unique importance to a long MOB structure.

Utilizing new and forthcoming computational tools, Kvaerner recommends the following follow-on work:

- Simulation of SeaBase global response using recently developed hydroelastic models. Representing the true nature of the highly flexible SeaBase concept, hydroelasticity represents the load changes that occur dynamically in the presence of structural motion or deformation.
- Validation of results from the new computational tools through well-planned hydroelastic model tests. Model tests are commonly used prior to constructing unique offshore structures.

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3.1.3 Independent Modules (WBS 4.1.3)

3.1.3.1 Resource

Bechtel National, Inc., (BNI) in California was the prime contractor with a major subcontract to McDonnell Douglas Corp., which later was acquired by the Boeing Company. BNI's offshore engineering group was originally PMB Engineering, Inc., which became a wholly owned subsidiary of Bechtel International.

3.1.3.2 Advancements

IMMOB Concept. Simply referred to as the Independent Modules MOB (IMMOB), this system concept consists of three extremely long semisubmersible steel modules, each about 488m (1600ft) long, that are dynamically positioned relative to one another (Figure D-5). The dynamic positioning system provides both absolute positioning of the overall MOB and relative positioning of each module. An easily raised drawbridge spans the nominal 7m (25ft) gap between modules and creates a continuous airplane runway. The individual modules are functionally connected via a sliding drawbridge/docking mechanism that does not provide any structural resistance. Disconnecting the MOB is simply accomplished by raising the drawbridges and powering the modules apart. Each module can then easily operate independently as a mini-MOB whenever fixed-wing air operations are not required. Each module carries a payload of over 100,000 tons and provides deck space for over 40 million cubic feet of equipment.

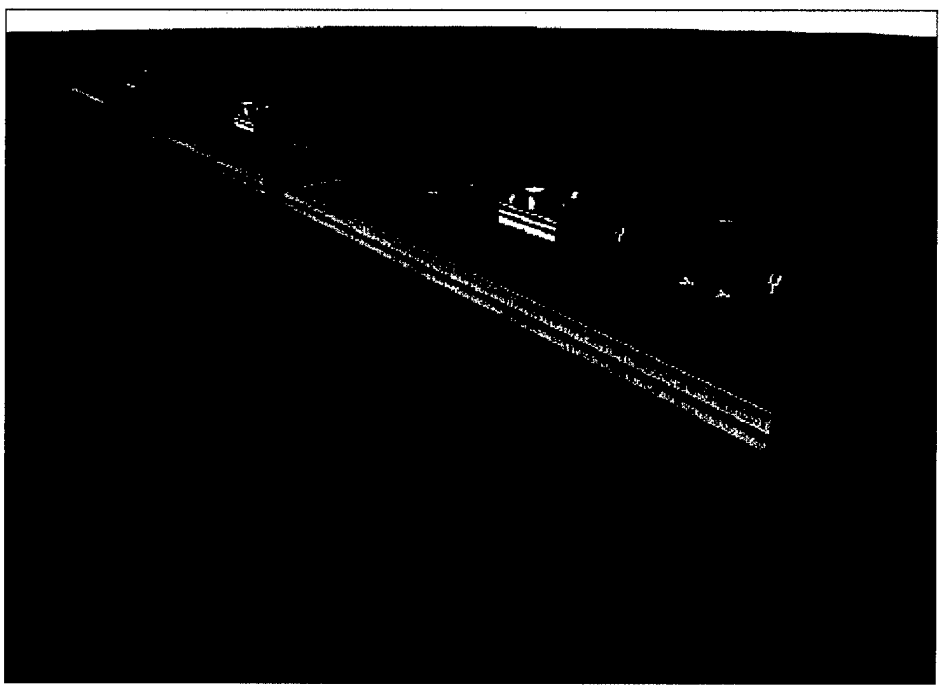

Figure D-5. Independent Modules MOB Concept.

The two unique characteristics of the IMMOB concept that distinguishes it from the other concepts are the three very large modules and lack of (problematic) connectors. Initial analysis indicated that the modules have such significant inertia that wave-induced motions are very small. This realization led to the idea that the modules could be allowed to move relative to each other and that a simple sliding deck bridge could be conceived to absorb this motion at the interfaces. Unique critical performance issues included the bridges and auxiliary mooring system that absorb the relative motions, and the dynamic positioning (DP) system that keeps the relative motions small enough for accommodation by the bridges.

Longest Feasible Module Length. A rigorous strength and fatigue analysis of a 1600 feet long independent module was performed using procedures that are similar to those used for permanently moored semisubmersible floating production units. The results indicated that strength is assured with conventional ship-type stiffened plate structure.

The large length of each module of this three-module concept is much greater than the current state-of-art for semisubmersible construction. However, there is a definite benefit to this long length because it results in little (if any) resonant motion in even long-period swell waves. For module lengths in excess of 2000 feet, required plate thickness is at or above the limits for practical fabrication. This indicates that a maximum MOB length of 6500 foot could be obtained with a three-module MOB configuration.

Therefore, depending upon the final requirements of MOB length, the number and length of the individual modules can be selected with some degree of flexibility keeping in mind the fact that it is advantageous to keep the modules as long as possible to minimize wave induced motions. BNI developed a very extensive engineering design basis with operating requirements and metocean criteria for use in developing load cases and time histories for the analysis on IMMOB motions and structural stresses.

Dynamic Positioning. The key issue for this concept is the performance of the dynamic positioning (DP), which must be capable of unconditionally maintaining alignment for the three modules during fixed wing aircraft operations. The DP system consists of power generation, thrusters, sensors and an automatic control system which together provide the 200,000 horsepower and about 5 million pounds of thrust to locate and orient each module. This system has been developed with the premise of using existing hardware, and each of the elements included in the current concept is proven in the marine industry.

Engineering analyses of the current system indicate that it will exceed the current Mission Need requirements and will maintain alignment of the modules in environments more severe than Sea State 6. The efficiency of such a unique multiple-module DP system determines overall fuel costs for operating this system platform concept. For further information refer to Section 3.2.4, WBS 4.2.4 on Multiple-Module DP later in this appendix.

Module Interface. The IMMOB concept and, for a lesser extent, all modular concepts require specialized structures that functionally connect adjacent MOB modules. Figure D-6 shows an aircraft bridge, a cargo bridge, fenders, and a mooring connector, all spanning the gap between modules.

The Aircraft Bridge provides angular and translational continuity in the runway while allowing some relative motion between MOB modules. The drawbridge bridges are counterweighted so that they rise if there is an equipment failure. They are held down in position by redundant constant tensioning devices.

The Cargo Bridge provides for transferring cargo and personnel at the lower deck level between modules. This 2-lane wide drawbridge is essentially a smaller version of the Aircraft Bridge. Large conventional

rubber dock fenders are provided at the end of the module to absorb any impact from possible collisions between modules while operating in close proximity.

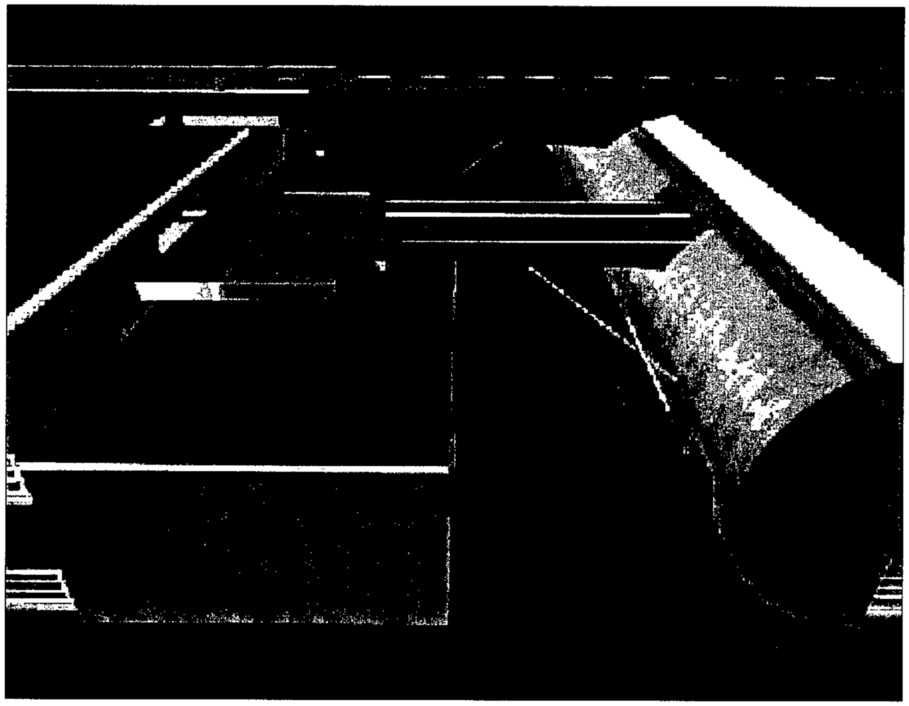

Figure D-6. Component Concepts for Module Interface.

A low capacity, auxiliary mooring connector has also been designed. This complimentary connector is intended to act in place of the dynamic positioning system during lower sea states to save fuel costs. It consists of a rigid strut on each side of the modules to take surge and yaw motions, and chain spring lines that run diagonally between the modules to resists relative sway forces (Figure D-7). The connector is stiff enough to hold the modules relative to each other under the constant loads from low level winds and currents. It is also flexible enough to allow the modules to move relative to each other under mild to moderate wave-induced motions. As a result, the mooring system elements are relatively small and well within existing experience in the offshore industry. Analysis indicates that the system can even perform adequately through mean Sea State 7.

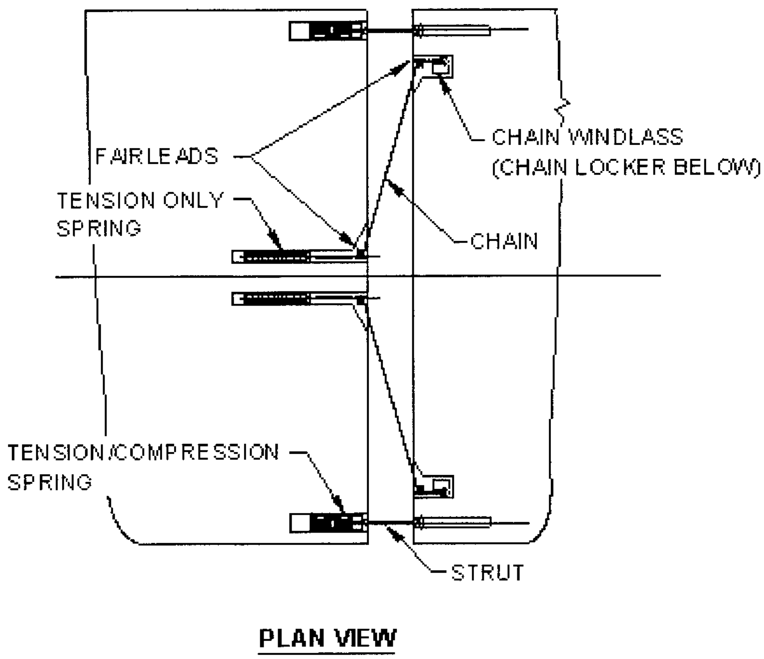

Figure D-7. Auxiliary Mooring Connector (plan view).

If the weather should deteriorate to the point where air operations can no longer be carried out and the bridge angle approaches its limit, the modules can be easily disconnected by casting-off the auxiliary mooring elements, raising the bridges, and driving the modules apart with the DP system. The ability to safely disconnect could be a useful feature of this concept for emergency scenarios, and it is not shared by the other platform concepts.

Runway Irregularity Limits. It was important to verify that relative motions between the modules do not seriously impact air operations. The principal motion of concern was the vertical angle between the bridge and the module created by relative heave and pitch. The first task in verifying that the aircraft could accommodate this angle was to establish a criterion for the maximum abrupt change in slope that the aircraft can accept.

When the airplane is rolling down the runway and encounters an increase in runway slope, the landing gear must accelerate the fuselage upwards. This loads the landing gear, the wing spar, and the engine pylons. If the slope change and resulting acceleration is too large, it will overstress the aircraft structure. McDonnell Douglas (now Boeing), who designed and who manufacture the C-17, performed a dynamic structural analysis of the C-17 when encountering the small slope changes (runway angles) at the runway bridges. They found that the allowable runway angles depend on a number of variables including aircraft weight, speed, and whether the airplane is landing or taking off. They estimated the maximum allowable runway vertical angle to be two degrees.

Issues Remaining to be Resolved. Before continuing with any further work on MOB development, one must prepare comprehensive design criteria. These design criteria must include the following:

- Further advancement and evaluation of dynamic positioning systems, emphasizing robustness to all possible excitations, and high long term reliability
- Specific operational requirements, including the type of material, supplies, and personnel and the length and type of operations associated with this material and personnel.
- General requirements for payload, storage volumes, flight deck areas, etc., based on the operational requirements.
- Metocean criteria for the worst case geographic regions of operations
- Typical storage sites where minimum drafts can be defined.
- Potential deployment sites to see if there is any restriction on operating draft.
- Rate of deterioration of cargo transfer with increased vessel motions

While useful, present hydrodynamic models and calculations are not considered sufficiently accurate for properly computing the air-gap or water impact on the underside of the deck. The reliability and fuel consumption of the dynamic positioning system needs to be fully assessed.

The MOB must accommodate significant heavy equipment below the deck and near the water line. This includes, for example, ship mooring equipment, platforms and ramps for RO-RO loading, elevators for lifting cargo, and equipment and wall elements for providing breakwater protection for small boats. All of these items are large, but yet may need to be stored out of the wave zone.

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3.1.4 Concrete/Steel Modules (WBS 4.1.4)

3.1.4.1 Resource

Aker Marine Contractors a.s. (Aker) in Norway with involvement of Aker Maritime in Texas and University of Trondheim in Norway.

3.1.4.2 Advancements

Concrete MOB. Simply referred to as the concrete MOB, this system concept consists of four semisubmersible modules, each 381m (1250 ft) long, consisting of a steel deck (dark grey) and concrete lower hull (light grey pontoons and columns) as shown in the figure below. The necessary cross-bracing between pontoons of the hull are also made of steel. Modules are nominally connected by elastomer bearings and post-tensioned cables.

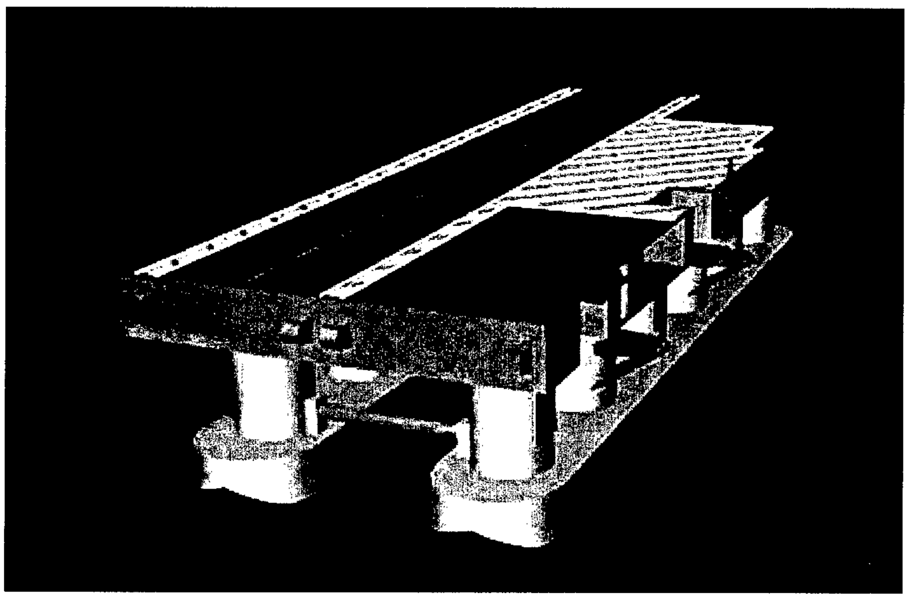

Figure D-8. Concrete/Steel Semisubmersible Modules (one module).

Based on preliminary finite element analyses, the required concrete thickness and the densities of reinforcing steel are well within the state-of-practice for existing offshore concrete structures. Since a concrete structure would weigh more than an equivalent steel structure, a hybrid concrete/steel structure offers a compromise to this weight difference. The lighter steel deck versus the heavier concrete deck also assures a more stable MOB structure by lowering the center of gravity.

The Concrete MOB concept is able to support aircraft operations through Sea State 6. Above this sea state, the MOB is disconnected into four separate modules to avoid over-stressing of the connector arrangement. The MOB is also disconnected during transit.

In the concept-screening phase, Aker determined that hinged flexible connections were required between adjacent modules. This connector design evolves out of previously designed large-scale connections

between concrete hulls and deck structures for previous fixed and floating concrete platforms. The MOB connector use an elastomeric bearing arrangement for desired force transfer between modules (longitudinal forces, vertical shear forces and horizontal shear forces between modules) while at the same time establishing a degree of freedom for pitch and yaw motions.

Assembly Line Construction. Choosing concrete over steel could result in significantly lower life cycle costs with respect to issues such as fatigue life, blast resistance, and ease of in-situ construction/repair. A key to this latter advantage is the innovative ability to slip form the structure on the water using a floating construction scenario. This allows the MOB to essentially be constructed to any length and breadth without consideration given to the confining size of even the world's largest dry docks.

Based on proven technology, Aker Maritime established a "construction assembly line" for building the concrete hulls. Shown in Figure D-9, the latter method is also well proven and tailored to US coastal conditions and the enormous size of the MOB modules.

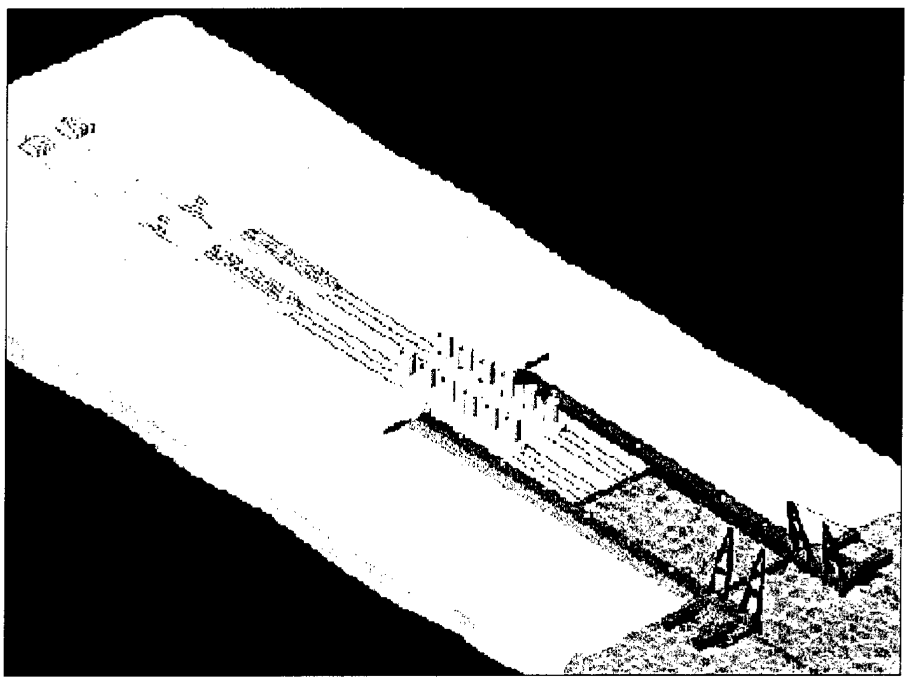

Figure D-9. Assembly Line Construction of Semisubmersible Hulls.

The production line offers the possibility of constructing the hull at "work stations" on dry land on horizontal skid-ways. When the planned work is completed at one station, the structure is skidded to the next. When the concrete hull is completed, it is "lifted" by the use of water from the last "on land " workstation to a floating position. The structure is then moved to the "deep water" end station. The water is lowered to sea water level and the hull module is permanently afloat. The deck sections are lifted onto the hull by shear-leg type cranes at this end station where all structural connections and mechanical hook-up between hull a deck are also completed.

An important advantage of the assembly line principle is that the units occupy a minimum of time in the

dock facility. Consequently, the construction schedule can be reduced compared to conventional dock construction. The estimated total construction schedule for four hulls, i.e., one complete MOB, is 4 years utilizing the assembly line method. Subsequently a new MOB (4 modules) can be completed off this (one) assembly line every two years. The steel decks are brought in from other fabrication facilities. This construction methodology may be adaptable for fabrication of steel semi-submersible hulls.

Advantages of Concrete over Steel. With an intended service life of 40 years without docking for periodic maintenance, fatigue can be a critical issue for steel-hulled MOB concepts. By introducing post-tensioned concrete as the material for the lower hull, fatigue becomes a non-critical issue. Theoretical calculations for the MOB concept and in-service experience from the harsh North Sea environment, has demonstrated that post tensioned concrete structures have excellent fatigue strength. Also unlike a steel hull, the concrete hull is very stiff, which will reduce the effect of structural deformation under the loads (hydroelastic effects).

Offshore concrete structures are presently in place with a service life of 70 years (Troll A), and no fatigue damage has been revealed on existing structures that have been in service for more than 25 years. As a direct result of these long lives, durability and maintenance also become non-critical issues for MOB. The key success factors for construction of durable concrete structures are careful material selection and quality commitment in all stages of concrete production and concrete construction.

The acquisition cost for four hull units, i.e., a total MOB, is at the same level for steel and concrete. The life-cycle cost is however about 17% less for concrete compared to steel.

Alternative Concrete Concept. Eight different concepts were considered in a concept screening study before the selected semisubmersible configuration was chosen. Given certain changes in the MOB mission requirements, such as larger cargo storage space, the contractor feels that certain other concepts, better tailored for concrete, may be preferable. For example, with respect to certain MOB design challenges, a single monolithic displacement hull configuration (Concore) may be a better alternative for concrete than a semisubmersible configuration.

Such a unique configuration would consist of a rectangular concrete displacement hull, approximately 890m (2920 ft) long, with steel deck cantilevered out 317m (1040 ft) beyond each end of hull. This rectangular displacement hull is much cheaper to build, has tremendous torsional stiffness/strength, and provides a very large cargo capacity. However, a single-hull MOB platform does not offer sufficient mission flexibility, and the modular semisubmersible configuration was pursued instead.

Issues Remaining to be Resolved. Aker sees no showstoppers for its concrete/steel hybrid MOB concept, although there are some critical issues that need further investigation. Outstanding technical risks involve heavy displacement and powering requirements. The concrete/steel hybrid MOB displaces on average twice as much as a steel only semisubmersible based MOB. As such, the cargo carrying capacity is slightly reduced, and the power requirements for transiting and positioning concrete/steel hybrid MOB modules would be larger.

Aker's hydrodynamic analysis revealed that air gap calculations, or the risk of wave slamming against the underside of the steel deck, had to be studied in more detail. (This applies to all of the concepts.) Advancements in this area were initiated under the Design Tools product area (see Appendix C).

Within the limited time frame dedicated to connector design, Aker developed a connector concept with a stiff center connector and elastic wing (port and starboard) connectors. The connector concept has been through only a "first level" feasibility check. Additional investigation and development work is required

to ascertain the real potential of this connector concept and its operation in heavy seas.

3.1.4.3 Products

1. Aker Maritime Contractors a.s., Barge Type Concept (ARCOMS), 23 December 1997.
2. Aker Maritime Contractors a.s., Concept Screening Report (ARCOMS), 28 November 1996.
3. Aker Maritime Contractors a.s., Concept Study (ARCOMS)- Drawings, 17 November 1997
4. Aker Maritime Contractors a.s., Concept Update (ARCOMS), 19 December 1997.
5. Aker Maritime Contractors a.s., Connection Arrangement (ARCOMS), 11 May 1997.
6. Aker Maritime Contractors a.s., Construction Report (ARCOMS), 7 April 1997.
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8. Aker Maritime Contractors a.s., Delivery and Operations, 7 April 1997.
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10. Aker Maritime Contractors a.s., Global Performance (ARCOMS), 1 April 1997.
11. Aker Maritime Contractors a.s., Hydrodynamic Analysis Tools-Validation Against Model Testing - Final, 31 October 1997.
12. Aker Maritime Contractors a.s., Hydrodynamic Global Performance, Concrete Semi, 31 October 1997.
13. Aker Maritime Contractors a.s., Inspection / Maintenance / Repair (ARCOMS), 8 April 1997.
14. Aker Maritime Contractors a.s., Mechanical Outfitting Design Report (ARCOMS), 7 April 1997.
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16. Aker Maritime Contractors a.s., Positioning and Transit (ARCOMS), 1 April 1997.
17. Aker Maritime Contractors a.s., Structural Analysis and Design (ARCOMS), 7 April 1997.
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19. Aker Maritime Contractors a.s., Thruster Confirmation Report, 19 December 1997.
20. Aker Maritime Contractors a.s., Topside Arrangement/Equipment (ARCOMS), 1 April 1997.
21. Aker Maritime Contractors a.s., US - Construction (ARCOMS), 8 October 1997.
22. Aker Maritime Contractors a.s., Weight and Stability Report (ARCOMS), 3 April 1997.
23. Rognaas, G., J. Xu, S. Lindseth, and F. Rosendahl, MOB Concepts – Hybrid: Concrete Hull and Steel Topsides, Third International Workshop on Very Large Floating Structures (VLFS '99), Honolulu, Hawaii, September 22-24, 1999.

3.1.5 Evaluation of Technical Feasibility (WBS 4.1.5)

3.1.5.1 Resource

The University of Hawaii (UH).

3.1.5.2 Advancements

This was a parametric study aimed at evaluating how sensitive MOB platform dynamic motions and connector loads were to variations in the module and platform geometry. A serially connected semisubmersible platform was defined as the reference concept using semisubmersibles 300 to 500m long. The connection ranged from a pseudo-connection, where the modules are aligned solely by dynamic positioning, to various mechanical connectors such as hinges, gimbals, etc.. The objective was to qualitatively understand how variations in the connectivity (elasticity, restrained degrees of freedom) and module geometry (length, column and pontoon dimensions, etc.) affected the platform dynamics.

The University of Hawaii conceptualized a number of innovative MOB concepts that departed radically from the reference concept. These concepts were typically designed to alleviate some fundamental performance problem. For example, any platform that uses hinged connectors will exhibit very large connector loads associated with the platform's torquing and horizontal bending response modes; replacing the hinges with gimbals would reduce those problem loads but correspondingly increase the runway dynamics could be unacceptable. And while some of the conceptual designs were clearly impractical, their performance represents an outer bound for all design modifications in that same direction.

One such innovative concept is depicted in Figure D-10. For this duck-toed concept, the pontoons were rotated in an effort to reduce connector forces due to horizontal bending for near-beam incident seas. In reality, the innovation only reduces the vertical connector force by 20% as compared to the "standard" serially connected semisubmersible concept. This is not a sufficiently significant improvement given the lack of mobility that results from the duck-toed configuration.

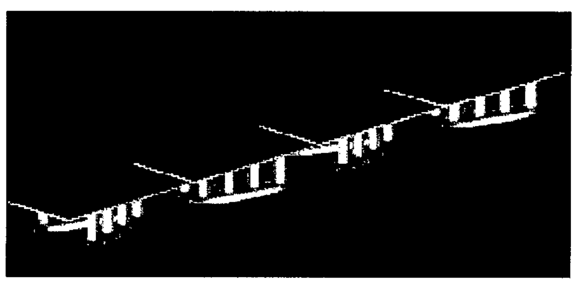

Figure D-10. Duck-Toed MOB Concept.

A 1500m long floating structure has no precedent, and therefore we have no operational or failure experiences with such a long connected structure in the open ocean. As such, significant thoroughness and accuracy is required to analyze these unprecedented structures, and to properly define that analysis in the *MOB Classification Guide*. This study contributed to that important topic by isolating the particular global response characteristics and loads that most dominate any module/connector geometry.

Many of the required computational tools for analyzing unique MOB are not currently available. Products that are available require modifications to properly deal with some of the unique structural

characteristics and environmental aspects of some of the more unique MOB concepts like Float's pneumatically stabilized platform.

As part of this study the University of Hawaii developed a user-friendly, graphically based computer program called HYDROMOB. This simplified model is specifically tailored for the expedient parametric dynamic evaluation of alternative MOB configurations from a basic design. This evaluation tool allows designers to optimize the motions and connector loads of different concepts versus a variety of parameters such as: number of modules, component dimensions, etc. HYDROMOB is fully described in the Design Tool product area (Appendix C).

3.1.5.3 Products

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2. University of Hawaii at Manoa, Development of a Windows-based Computer Program HYDROMOB and Response Characteristics of some MOB Designs Report, December 1998.
3. University of Hawaii at Manoa, HYDROMOB – MOB concept evaluation tool - Simulation Models & Data.
4. Very Large Floating Structures (VLFS) Conferences. With funding from the National Science Foundation, the University of Hawaii hosted the First International Workshop on Very Large Floating Structures (VLFS) in 1991 in Honolulu, Hawaii. This workshop focused on technological innovations needed for siting various land-based activities onto very large floating structures. With funding from the Office of Naval Research, the University of Hawaii hosted the Third International Workshop on VLFS in Honolulu, Hawaii in 1999. MOB was a major participant in this third workshop with over 60 papers.

3.2 Components (WBS 4.2)

Much of the innovation required to ensure technical feasibility of a MOB must be directed towards critical components of the MOB. Rather than develop innovative component concepts that are unique to each system concept, this Program developed generic versions of each of these critical components, applicable to any system concept.

These component concepts include the following:

- Inter-Module Connector Technology
- Elastomeric Connector Material
- Compliant Connector
- Multi-Module Dynamic Positioning System
- Control Strategy for Dynamic Positioning
- Pneumatically Stabilized Platform
- Suction Pile Anchors
- Lightweight Decking
- Open Sea Cargo Transfer

These studies are described in the following sections.

3.2.1 Inter-Module Connector Technology (WBS 4.2.1)

3.2.1.1 Resource

Brown and Root, Inc. (B&R) in Texas developed a rigid MOB connector and then compared its features to a spectrum of connector types appropriate for MOB. B&R collaborated with Atlantic Research Corp (ARC) of Virginia. The University of Maine analyzed the rigid connectors and compared their performance to model scale experimental data.

3.2.1.2 Advancements

A spectrum of connector types. For many of the system platform concepts, a large capacity structural connection is required to link individual floating modules into a larger MOB platform to provide a long runway for landing fixed wing aircraft. These connectors are generally the weak link structurally. This study assumed independence between the performance of the local connector component and the global platform system because that allowed for an assessment of each type of connector independent of the module characteristics.

B&R gathered information on all types of marine connectors, including those currently being developed for connecting modules of the system platform concepts. Applicable types of connectors were classified into a logical spectrum of marine connectors useful for connecting any two MOB modules. There are six components of relative motion between modules, each of which can be rigid, compliant or fully released. As such there are 18 possible choices of connector type by this classification category alone. B&R also classified marine connectors according to the different types of force resistance and methods of connection or disconnection.

Given upper bound limits of motion for each connector concept, connect/disconnect procedures were found to generally be impossible above Sea State 7 conditions. As such, safe modes of failure are needed to avoid sinking the whole MOB when only one module is damaged. Constructability of the connector was a key issue for all potential connector concepts. Another major concern is the distribution of the large forces from the connector into the module hull structure.

Rigid Connector. B&R continued development of a MOB rigid connector. Finite element structural analysis showed that it was possible to transfer large forces from the rigid connector into the hull. B&R also employed the elastomeric tubular members developed by ARC as a compliant interface between the rigid connector and the hull. This kind of compliance aids in spreading forces evenly around the connector face, in facilitating mating between parts with tight tolerances, and in absorbing impacts.

Connector Forces. The University of Maine analyzed model test data for tests done at NSWC-Carderock (under DARPA sponsorship in 1994) for a rigidly connected MOB. Those tests found very large forces for the four connectors. Their analysis resulted verified that these measured forces were accurate and indeed representative of a full-scale MOB.

The University of Maine subsequently analyzed a second set of data for tests done at NSWC-Carderock in 1996 (again, under DARPA sponsorship) for a hinge-connected MOB. While the physical models were not built with the intention of measuring accurate connector loads, the measurements that were taken revealed much-reduced forces in the connectors. The maximum forces measured 215,000 tonnes in axial tension and 77,000 tonnes in shear. These forces vary greatly on the type of hinge connector, the connector stiffness and the wave heading.

3.2.1.3 Products

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2. Brown & Root, Inc., MOB Connector Systems - Design Drawings, 17 May 1999.
3. University of Maine, ABAQUS Computer Model of the Rigid Connectors used in NSWC-Carderock Experiment.
4. University of Maine, ABAQUS Model of Rigid MOB as used in NSWC-Carderock Experiment.
5. University of Maine, Connector Load Dynamics for a MOB (based on B&R concept), 1 January 1998.

3.2.2 Elastomeric Connector Material (WBS 4.2.2)

3.2.2.1 Resource

Atlantic Research Corporation (ARC) SEQA in Virginia was the prime contractor and is the developer of three-dimensional (3D) braided composite material. The Naval Surface Warfare Center, Carderock Division (NSWC-CD) in Maryland molded the elastomeric material and performed the model verification tests. The NASA Goddard Space Flight Center in Maryland provided mechanical designs. Under subcontract to ARC, the University of Delaware developed material constitutive models, the University of Maine analyzed the test configurations, and Polygon Associates (now called Fiber Architects) in Pennsylvania performed finite element analysis.

3.2.2.2 Advancements

ARC's technical focus was the flexible component for an inter-module MOB connector. ARC chose to use elastomeric braided composite tubes as the basis for a their flexible component. This connector material is not meant to provide the "latching mechanism" between MOB modules, but rather act as a flexible foundation for attachment of any "latching mechanism"/connector to a MOB module hull.

For example, in cooperation with ARC, Brown & Root showed that their rigid connector could become quite flexible by utilizing this elastomeric material at the interface between their connector and a module hull. Flexibility in the connector helps to more evenly distribute forces and improve load transfer. It also allows mating parts in the connector to fit together with less attention to matching tolerances. Flexibility also provides the overall structural compliance need to make a long MOB feasible.

Basic Compliant Building Block. Originally developed by NASA, the basic building block for ARC's compliant couplings is shown in Figure D-11. When bent the rods between the two blocks allow compliance in two translational and two rotational degrees of freedom. NASA envisioned these rods to be steel cables, while ARC envisioned the rods to be elastomeric tubes. By utilizing various combinations and arrangement of this building block, it is possible to build compliant couplings with any number of degrees of freedom.

For a hinge-type connector along the deck of a MOB, one would build assemble several of the basic building blocks into a long linear arrangement as shown in Figure D-12. Shown at the top and bottom of the figure, each faceplate of this long assemble connector is allowed to rotate relative to one another along its length. By easily bending the composite tubes connecting the two faceplates, the action becomes much like a large door hinge. And just like a large door hinge, no other motions are allowed. More composite tubes are grouped at the ends of the long connector to resist better any tearing action in the hinge.

By rigidly attaching each faceplate to the top deck edge of adjacent MOB modules, this type of connector allows a large amount of relative pitch between MOB modules with practically no relative heave, surge, sway, roll, and yaw. As such the MOB modules are restrained in all degrees of freedom relative to one another except pitch. These are desirable compliant characteristics for inter-module hinge-type MOB connectors. The number, length and thickness of the elastomeric tubes in the compliant couplings can be further varied to accommodate the expected stress field and the desired displacements of the MOB modules.

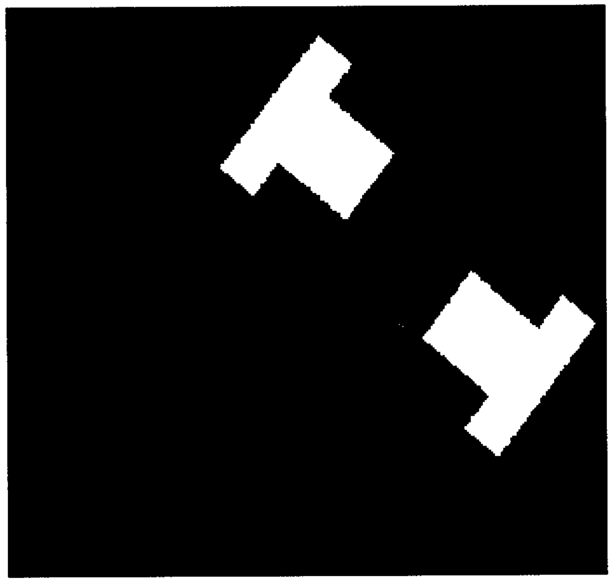

Figure D-11. Compliant Coupling Building Block with Lateral Deformation.

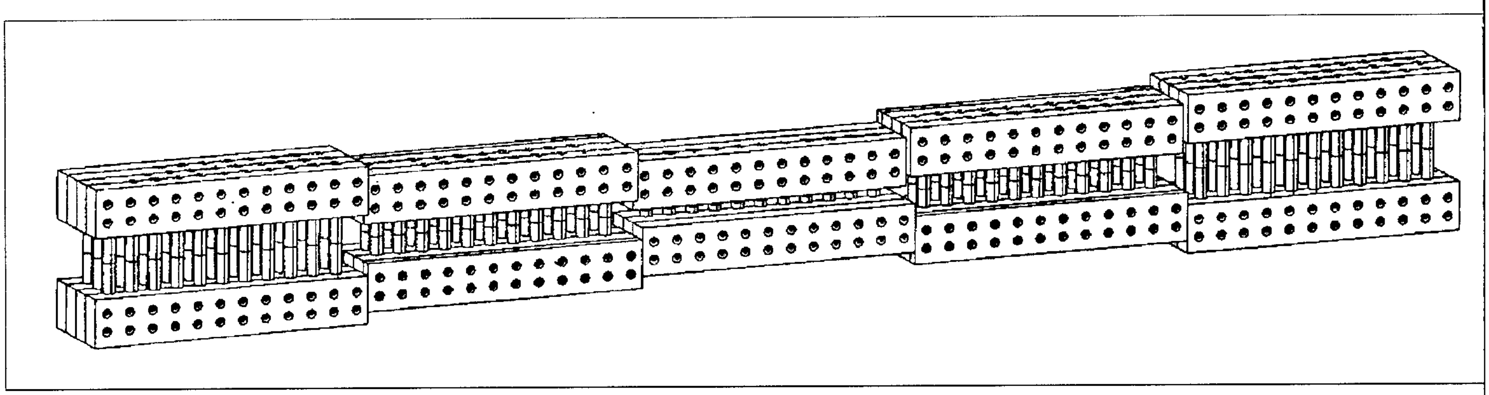

Figure D-12. Scale Model of Hinge-Type Deck Coupling.

Material Development and Characterization. The ARC team developed a new type of composite material, namely 3-D through-the-thickness braided carbon fiber, encased in a urethane elastomer matrix. ARC established fabrication parameters and processes for manufacturing the composite material into elastomeric tubes for use in the compliant coupling building blocks. They employed a fabric geometry model to characterize the behavior of the braided composite material within the elastomeric tubes. Through various laboratory material tests, they further characterized the engineering properties of the elastomeric tubes, including constitutive material, material aging and bending fatigue properties.

The ARC team developed local connector numerical models to analyze the dynamic force characteristics of connector concepts. They also performed scale-model structural laboratory tests of a compliant connector configuration with steel cables to validate nonlinear finite element models of the connector.

In theory, compliant materials offer significant force reduction via dynamic force compliance and/or nonlinear material resistance. Validating this theory required careful numerical analysis using fine resolution numerical models of the connector. By correlating these models with experimental test data specifically collected for this purpose, the key static and dynamic properties of composite elastomeric tubular members became apparent.

Issues Remaining to be Resolved. ARC found no "show-stoppers" to creating safe and reliable inter-module MOB connectors that would reduce the overall connector forces by well over an order of magnitude. However, to better understand compliant couplings that utilize elastomeric tubes, ARC proposes various additional tasks. These include the following:

- Sub-scale structural laboratory tests of a compliant connector configuration using elastomeric composite tubes to validate nonlinear finite element models and to get correct connector stiffness.
- Global analysis of entire connected MOB with correct connector stiffness to get global displacements at connector.
- Full-scale analysis of connectors using correct material stiffnesses of elastomeric tubes with refined finite element analysis of tubes to predict tubular buckling limits.
- Refine design of connectors including quantity of tubes, tube arrangement and material architecture based on global analysis results.
- Full-scale fabrication and test of connecting module (does not have to be an entire MOB connector just a segment of one).

A key question concerning the full-scale feasibility of this connector material is "What is the largest size that one can build these elastomeric tubes and how difficult is it to organize a matrix of them along the large faces of the MOB modules?"

3.2.2.3 Products

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3. Atlantic Research Corp., Design Drawings, 7 December 1998.
4. Atlantic Research Corp., Finite Element Modeling of 3-D Braided Carbon Fiber/Urethane Elastomer Tubes, 1 April 1998.

5. Atlantic Research Corp., Material Test Plan for the MOB Flexible Coupling Material System, 13 March 1998.

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10. Gignoux, H., Computational Model of Aquaculture Finfish Net Pens, M.S. thesis, Mechanical Engineering, University of Maine, August 1997.

11. Maguire, J., Structural and Deformation Analysis of Compliant Connectors, MS thesis, Mechanical Engineering, University of Maine, August 1999.

12. Thompson, L., Development of a Finite Element Model to Predict Dynamic Connector Loads for Dual Use Ocean Structures, M.S. thesis, Mechanical Engineering, University of Maine, August 1996.

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15. Weybrant, E., A Computational Study of Connector Force Dynamics in a MOB, M.S. thesis, Mechanical Engineering, University of Maine, May 1999.

3.2.3 Compliant Connector (WBS 4.2.3)

3.2.3.1 Resource

McDermott Technologies, Inc. (MTI), in Virginia was the prime contractor. The main technical performer was J. Ray McDermott, formerly McDermott Engineering Houston LLC (MEH), in Texas. Under subcontract, Regal International, Inc., (Texas) performed rubber curing tests, Offcoast in Hawaii performed comparative response simulations, Offshore Kinematics in Texas performed finite element analysis, and ERC of Texas performed other analyses. In addition, the Naval Research Laboratory (NRL) provided technical advice.

3.2.3.2 Advancements

The inter-module connector is the most critical component of McDermott's Hinged MOB Concept. Its feasibility, as well as other potential system platform concepts, is dependent upon successful development of an inter-module connector.

There has been extended discussion about whether their connected design should weather storms in a connected or unconnected state. McDermott's position has been to develop a connector which can weather the storms in a connected state, but which is simple and fast enough to disconnect and reconnect that the operator would seldom choose to remain connected in those conditions. McDermott's position has favored the connected state, yet with a connector design that would be simple and fast enough to disconnect and reconnect so that an operator would find it easier to disconnect in those conditions.

Rigid Hinge Connector. McDermott's original concept was to use simple rigid hinges on the upper hulls as shown in Figure D-13. The design for these rigid hinges allowed for rapid and reliable connection and disconnection using an innovative locking mechanism. The force developed in a simple hinge connector at Sea State 8 plus was estimated to be 180,000 metric *tons* (tonnes). Avoiding such immense forces would require disconnection of the platform at an intermediate sea state, with the corresponding undesirable effect on operations of lost time spent disconnecting and then reconnecting.

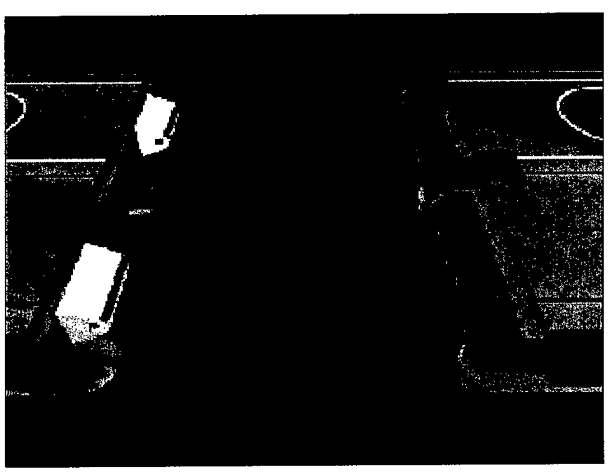

Figure D-13. Rigid Hinge Connector.

Alternative Connectors. Given such large loads, McDermott developed a series of alternative concepts for MOB connectors (ball-joints, bumpers, etc.) in an attempt to eliminate the disconnection requirement and permit connected operations in all sea states and all headings. First, releasing the additional rotational degrees of freedom in inter-module MOB connectors resulted in a significant reduction in forces. Then, providing flexibility or compliance in the remaining degrees of freedom resulted in even more reduction in force. However, the compliant devices must often be non-linear to avoid dynamic amplification (resonance) of motions in the structure.

McDermott proposed collapsible rubber cones as one way of achieving nonlinear (two-stiffness) resistance in a compliant connector. A stiff resistance (uncollapsed cone) is generally desirable for best operations in normal environmental conditions, and a flexible resistance (collapsed cone) is generally desirable for survival in extreme environmental conditions. These cones would be much larger than existing units, so the next question was whether such large and collapsible rubber cones could be manufactured. It depends almost exclusively on the ability to cure rubber, which in turn is highly dependent on the constituents used in the rubber compound.

McDermott used analytical methods to study the heat flow, optimize the curing and begin to understand how deforming rubber generates internal heat. They also performed four demonstration tests to show that thick wall rubber cones can be properly cured.

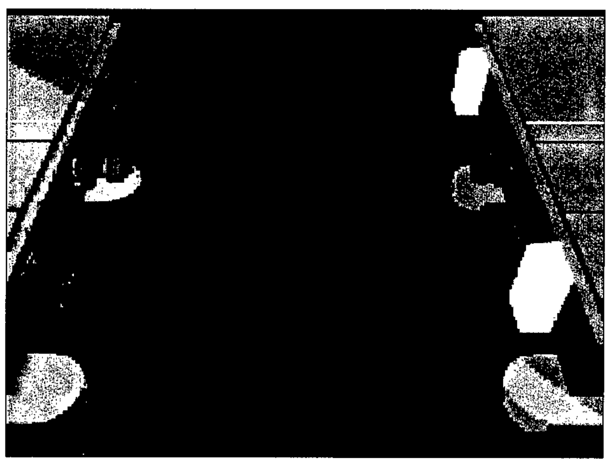

Figure D-14. Compliant Connector.

Figure D-14 shows McDermott's most recent compliant connector design, which includes a docking center ball-joint, and two outboard compliant hinges. The compliant connector allows the MOB modules to remain connected in Sea State 8 plus at any heading, permit disconnection at Sea State 7 and re-connection in Sea State 5. The compliant connector can be maintained and repaired at sea by retracting the connectors in-board and using resources on each MOB module to affect the repair.

The University of Hawaii's simulations suggested the value of damping in reducing motions and forces. This led McDermott to study the effect of damping and to incorporate damping elements in the compliant connector.

The result of all the compliant connector work has been a significant downsizing of the connector's size and weight, an incorporation of on-board maintenance options, and a reduction in impact forces during

connection and disconnection.

Issues Remaining to be Resolved. No showstoppers exist for designing, fabricating and repairing inter-module MOB connectors. However, the following issues could still use further research.

- Perform cyclical testing and develop thermal finite element analysis to estimate how various rubber compounds develop heat from its stress.
- Perform connected tests in a model test basin of the MOB with nonlinear compliant connectors that utilize mechanical dampers and/or buckling cones.
- Perform functional testing of the procedure for connecting and disconnecting the inter-module MOB connectors. These tests and related analyses should be sufficient to set design criteria about mating, relative position and closing velocity.
- Continue advancement of DP control systems

Dual-use. McDermott has proposed several commercial applications for its connector concepts. They propose using a simple hinge connector to hold a deck installation barge in alignment with a spar buoy for deep-water petroleum production. This will allow the entire deck unit (in one piece) to be slid onto the top of a spar buoy. Currently due to lifting limits, the deck must be installed in pieces.

In addition, McDermott proposes using a line of simple hinge connectors to assemble "dry-dock" type ships into an offshore cargo reloading port. The port is needed for transferring container cargo from a very large container ship into smaller container ships for dispersion to several ports.

3.2.3.3 Products

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3.2.4 Multiple-Module Dynamic Positioning System (WBS 4.2.4)

3.2.4.1 Resource

Bechtel National Inc. (BNI) in California was the prime contractor with subcontracts to Shatto Engineering in Texas, Nautex Inc. in Texas, and Raytheon Systems Inc. in Washington. Since the work was completed, BNI has eliminated its offshore engineering group and key members of the Raytheon team are now operating as GRD Associates, Inc., in Washington.

3.2.4.2 Advancements

Requirements Definition. The offshore industry regularly uses dynamic positioning (DP) to position an ocean platform precisely over its drill hole or a ship alongside a fixed structure. As such, current DP systems are rather reliable and well optimized for holding a single vessel in absolute position under the disturbing effect of metocean conditions. DP systems traditionally ignore cyclic high frequency motions that result from ocean surface waves and focus on counteracting low frequency drift type motions.

All candidate MOB system concepts require some form of dynamic positioning (DP) to maintain station. This is particularly useful for orienting the runway into the wind for flight operations and for aligning modules prior to making inter-module connections. No precedent exists for dynamically positioning a floating body the size of a MOB.

Most MOB concepts also require DP to move MOB modules together for connecting and separating modules during disconnection. For example, because it lacks structural connectors, the Independent Module MOB concept requires reliable DP operation for long-term relative alignment of the MOB modules. For this case, the DP system must actively maintain close relative positioning and alignment between each MOB module, all the time avoiding potentially damaging collisions between the modules. No precedent exists for dynamic positioning of multiple floating bodies relative to one another.

DP systems include software (command, communication and control computer programs) and hardware (power generation, thrusters and sensors). This particular study focuses on the hardware. Specifically, Bechtel characterizes the hardware required to dynamically positioning and aligning a series of large MOB modules and utilizes conventional linear software to control this hardware. The objective was to develop the basis for a multi-module Dynamic Positioning (DP) system that meets the unique positioning requirements of a MOB.

Characterization Hardware and Software. BNI and Shatto Engineering characterized a notional set of hardware and software for a MOB DP system, identifying the overall mechanisms for sensing, actuation, communication and control. The sensors monitor module position, speed, acceleration, and individual thruster performance plus metocean conditions such as wind speed and direction. The fully redundant automatic control system continuously processes the sensor information with fault tolerant algorithms that issue commands to the thrusters. Each thruster responds to its continuously varying commands with thrust magnitude and direction designed to precisely counteract the disturbing effects of the environment and keep the modules in correct location and alignment.

All of the components included in the DP system are available today off-the-shelf and have been used either by the Navy, the commercial marine industry, and/or the offshore petroleum industry. In particular, the newest class of super-cruise ships (currently under construction) use thrusters almost as large as those required for the MOB. Modern DP systems are triply redundant, meaning there are three fully

independent sets of hardware (computers, wiring, sensors, and propellers). Consisting of up to six separable modules, a MOB could have up to 18 redundant sets of hardware to satisfy this industry standard for system reliability.

Metocean Design Basis. BNI also developed models and methods for quantifying the metocean disturbances that control the design of the MOB DP system. BNI computed the static forces produced by steady wind, waves, and the dynamic forces computed by wind gusts, wave drift, and solitons. Solitons manifest themselves as a solitary subsurface long period wave whose spatial extent gives it different arrival times over a long multi-module MOB platform.

BNI computed steady current and wind forces using a computational fluid dynamics model (FIDAP). They compared results to wind tunnel results from tests conducted at the Naval Surface Warfare Center, Carderock. BNI concluded that CFD-predictions were useful for generating qualitatively informative 3D visualization profiles for current flow fields but not adequate for quantifying the current-induced forces and yaw moments on the MOB module. CFD predictions are much more reliable for air-related phenomena. For a MOB, adequate sensing and proper prediction of the temporal or spatial characteristics (especially the rate of change) in wind, current, and wave fields, as well as the resulting dynamic loads on the separate modules of the MOB, are both considered uniquely critical for reliable dynamic positioning.

The thrusters and power plant on all of the MOB modules must be sized to maintain a straight runway while resisting steady Sea State 7 metocean conditions.

Propulsion and Power Equipment. Nautex investigated the capacity of existing propulsion and power generation equipment to provide the required thrust for large semisubmersible modules. To resist expected wind, current, and wave drift disturbance forces, Nautex calculated that each MOB module needs eight fully rotating (azimuthing) variable speed thrusters located below the pontoon keels (Figure D-15). Each thruster is rated at 25,000 HP resulting in a maximum output potential of 200,000 HP per module. In shallow water, the thrusters can be retracted into wells in the pontoons to maintain a reasonable draft.

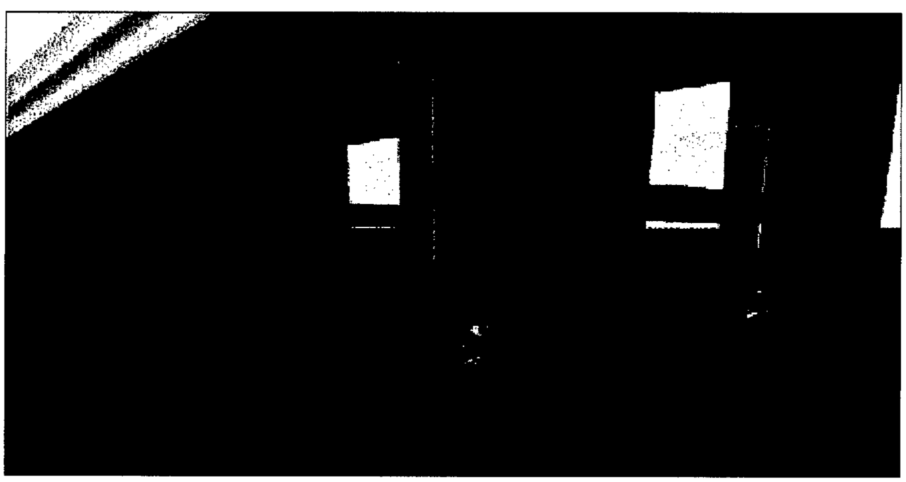

Figure D-15. Thruster Locations on a Typical Semisubmersible Module.

The eight thrusters on each module are capable of propelling the MOB module, at its transit draft, in excess of 15 knots. The required power generators, propulsion equipment, and thrusters required can be developed from off-the-shelf hardware. Power for the thrusters is provided by gas turbine electrical generators which have been allocated to provide a highly redundant, reliable system.

Extended DP Controller. Raytheon extended conventional DP software for controlling thrusters on one vessel (module) to software for controlling thrusters on multiple modules (Figure D-16). Raytheon used a traditional linear Proportional Integral Derivative (PID) controller in this DP software. The software included the application of steady and dynamic metocean forces, the mass properties of the vessel, the vessel position, data from metocean sensors, and the automatic control system in its computation of the proper thruster reaction forces that are need to position the MOB modules.

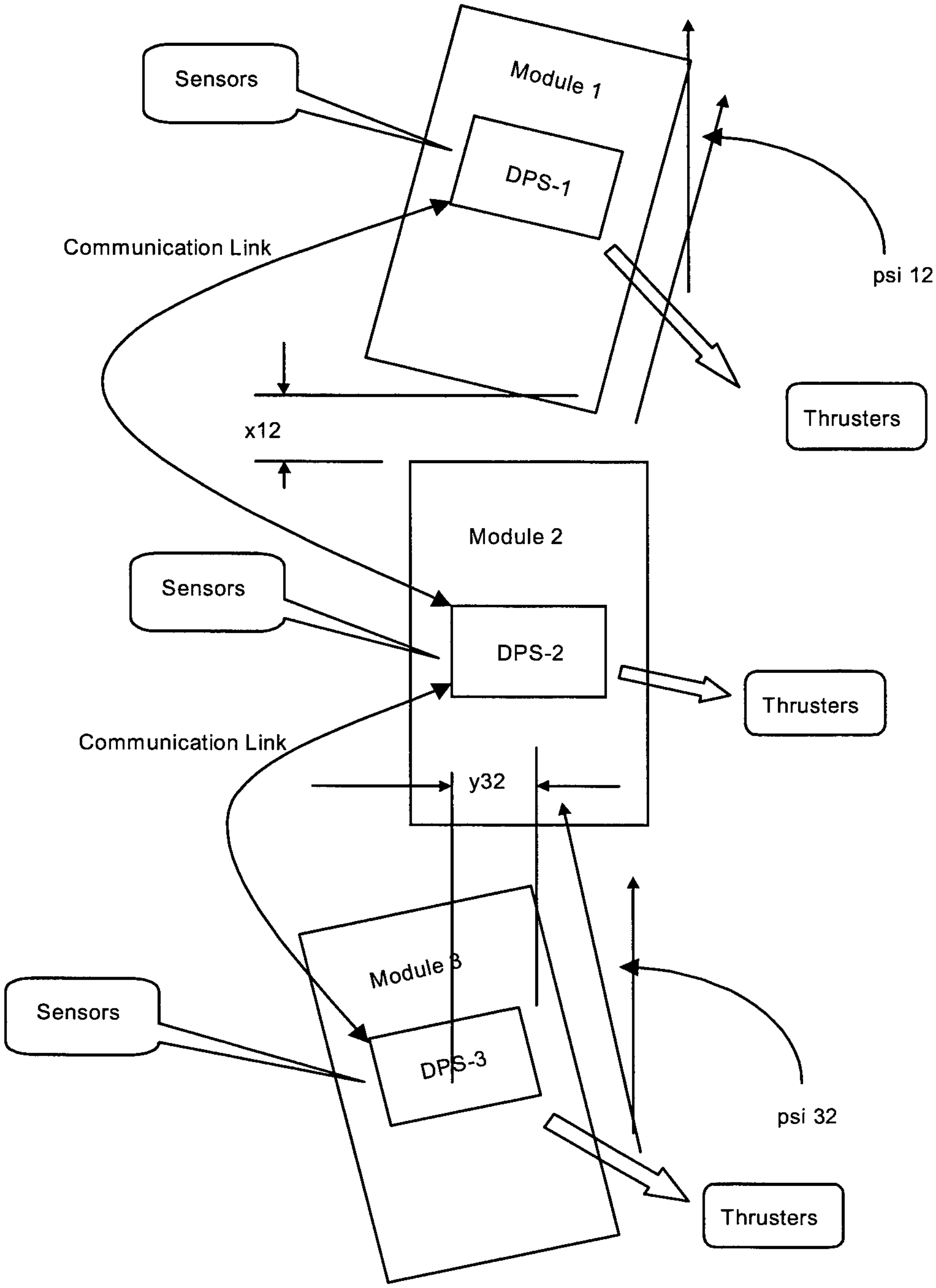

Figure D-16. Multi-Module Dynamic Positioning Control Concept.

The results of virtual simulations with Raytheon's software indicated that in most design metocean environmental conditions, motions and orientations, although not optimal, could be held to within required tolerances. To achieve these results, the parameters for the controller had to be carefully chosen for each given metocean environment and the controllers had to operate on the absolute (not relative) position and orientation of each MOB module.

The software had a difficult problem holding position and orientation of each MOB module against the disturbing force of a soliton. However, the degree of difficulty varied depending on the mathematical representation of the spatial and temporal occurrence of the soliton loads. There is not universal agreement on the physical nature, particularly the spatial and temporal character, of soliton loads. Finally, Raytheon's software with linear PID controllers was not able to closely control relative positions of the various modules when long-term wandering of the overall MOB was allowed.

Issues Remaining to be Resolved. Prior to fielding a multi-module dynamic positioning system, BNI and Raytheon recommend several actions including the following:

- a detailed system identification and fault tolerance study, over the full spectrum of MOB maneuvers and metocean conditions
- a concept of operations for independent operation of each MOB module, assembly/disassembly of MOB modules, and for emergency or contingent operations
- detailed specifications for DP system reliability and graceful degradation if, for example, significant power failure occurs
- active feed-forward measurement methods, such as a current meter to sense the presence of a soliton, a wave gauge and model to forecast severe waves, and inertial measurement unit to compensate for other forces acting on the MOB modules
- a physics study on how a soliton spatially and temporally applies its disturbing forces.

3.2.4.3 Products

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3.2.5 Control Strategy for Dynamic Positioning (WBS 4.2.5)

3.2.5.1 Resource

The University of California at Berkeley (UCB) performed as prime researcher with major assistance from Scientific Systems Corporation, Inc. (SSCI) (Massachusetts). UCB included control specialists from the Partners for Advanced Transit and Highways (PATH) and Naval Architects from the Engineering School. Dr. Allen Moshfegh, at the Office of Naval Research, who funds basic research in basic control theory, collaborated with the MOB program. This work is ongoing and currently scheduled for completion in the spring of 2001.

3.2.5.2 Advancements

Requirements Definition. As stated previously, dynamic positioning (DP) systems include software (command, communication and control computer programs) and hardware (power generation, thrusters and sensors). In this research thrust, we focus on a new generation of software for command and control of the hardware.

DP for a multi-module (segmented) platform such as MOB has never been built, and thus, has never been demonstrated as controllable. The technical challenge here is to position several MOB modules in close relative alignment to one another in the face of large inertial forces and spatially changing metocean forces. It must facilitate various operational modes including assembly/disassembly of modules, airfield orientation into the wind, and transit. It must transition from distributed control for disconnected (independent) MOB modules to centralized control for a connected series of MOB modules.

For adequate reliability, the control strategy must robustly avoid potentially damaging collisions between units yet keep them close and aligned straight when air operations are planned. Dynamic positioning system fuel efficiency and reliability are important life cycle cost issues.

Contrary to typical offshore petroleum industry requirements for absolute positioning over a drill hole, it is advantageous to allow the MOB to wander within a theater of operation. For example, since a floating object can naturally return to the same location every tidal cycle, one can potentially save a lot of fuel by allowing the MOB to wander with tidal currents. Furthermore, some wandering may be vital for vulnerability reasons. In other words, MOB needs DP software that is capable of more than absolute positioning; rather, it needs DP software that can reliably position MOB modules in close relative proximity to one another while allowing some accepted and pre-defined drift.

The work to develop a feasible approach for dynamically positioning multiple MOB modules was performed in four development thrusts:

- UCB and SSCI each developed broadly applicable control architectures and accompanying nonlinear controller theories and algorithms.
- UCB provide an "open architecture" simulation and evaluation framework, suitable for all MOB concepts.
- UCB demonstrated superior controller stability and performance for each of the controller algorithms through computer-based (virtual) simulation.

- UCB is demonstrating controller performance through a specially built experiment (physical simulation) using three 1:150 scale "generic" unconnected MOB modules. This thrust is ongoing and currently scheduled for completion in the spring of 2001.

Controller Architecture. To address mission handling and control as well as dynamic positioning of the platforms and safety issues, a three-layer software architecture that moves from discrete to continuous signals was conceived (Figure D-17). Using a hierarchical software structure, the nonlinear command and control allows for optimal and smooth performance of the DP over a wide range of transitional maneuvers such as assembly, disassembly, and realignment. By dividing control into local and global levels in which local information is "hidden" from the higher level controller, it is possible to achieve high performance without unnecessary complexity.

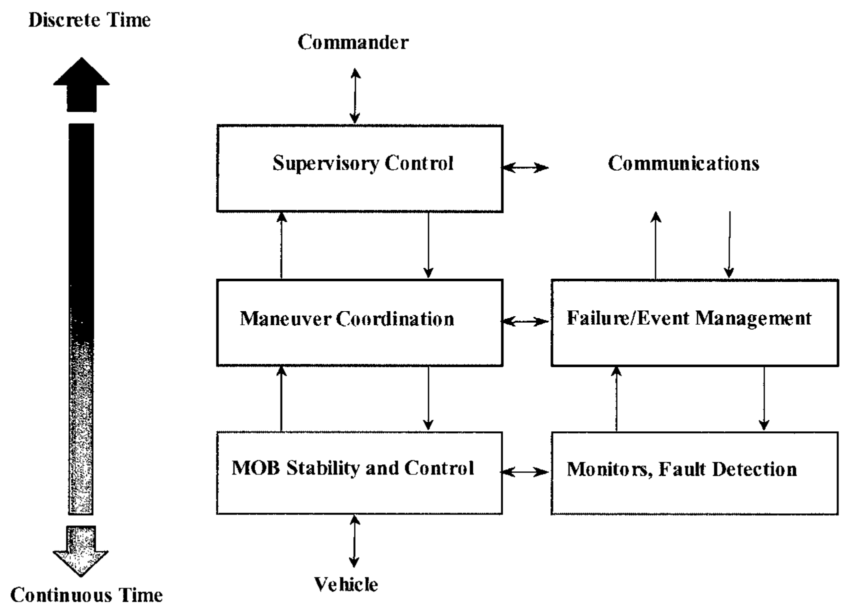

Figure D-17. Hierarchical Organization of the Control Architecture for the MOB.

At the *supervisory control layer,* shown in the top of Figure D-17, discrete commands are given to achieve high-level goals such as moving to a location, engaging/disengaging platforms, and assigning a coordinator/leader platform. This level deals with continuous signals, and interfaces directly with the platform hardware. It contains several dynamic-positioning algorithms, a thruster allocation scheme, and sensor data processing and monitoring for fault detection.

The *maneuver coordination layer* deals with control and observation subsystems responsible for safe execution of core maneuvers such as assemble, split, wind tracking, and go to a location. It provides dynamic reconfiguration, which also handles faults. The *MOB stability and control level* contains control strategies that the modules follow in order to minimize fuel consumption and maximize safety and efficiency (Figure D-18). It receives commands and translates them into specific maneuvers that the platforms need to carry out.

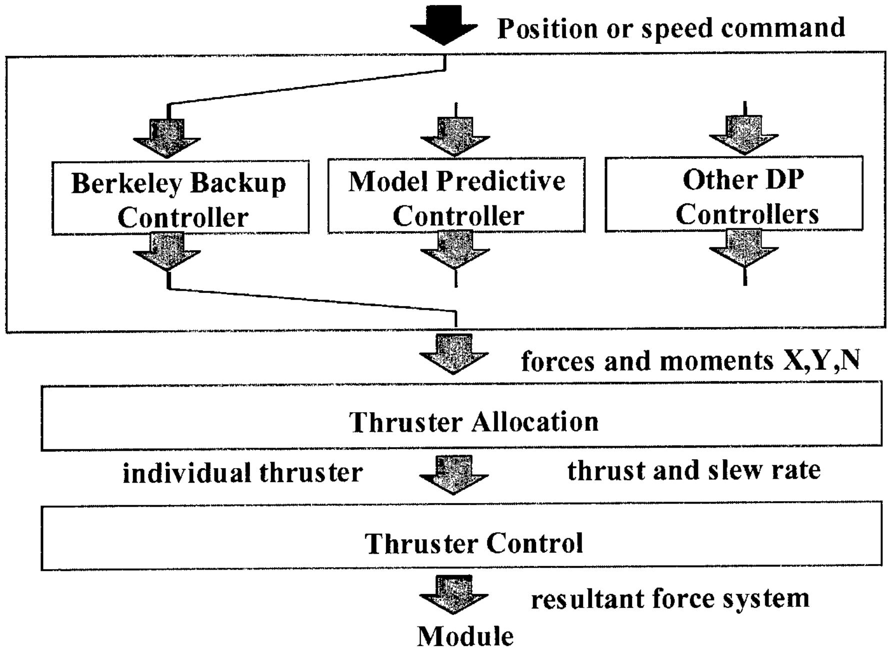

Figure D-18. Organization of the MOB Stability and Control Layer.

SSCI developed, coded, and virtually tested the Nonlinear Model Predictive Controller (NMPC). UCB developed, coded, and virtually tested an alternative control scheme known as the Berkeley Backup Controller (BBC). Both nonlinear controller schemes use both Leader-Follower and Leaderless candidate approaches to controlling dynamic position.

In the Leader-Follower approach, one MOB module is chosen as the leader and the other MOB modules follow the dynamics of the leader and maintain a pre-specified relative distance from the leader. In the Leaderless approach, the reference trajectories for all the MOB modules are derived by minimizing a cost function such as maximum deviation of any module or the total energy consumption. So far, the Leaderless control scheme was able to maintain the fastest alignment of platforms and the better alignment performance in time.

Virtual Evaluation Framework. For virtual evaluation of control strategies, UCB developed the SHIFT programming language to allow "dynamic networks of hybrid automata." This is precisely the dynamics of MOB DP, whereby components exhibit behavior that has continuous time phases separated by discrete even transitions. Control components are allowed to evolve independently or they may interact through their inputs and outputs to evolve a dynamic network. Using this dependent network, the MOB DP can easily provide for radical faults and emergency contingencies such as loss of one or more thrusters.

The SHIFT-coded virtual evaluation framework includes the virtual simulation computer model, metocean environmental disturbance submodels and appropriate control laws. The framework allows for many variations such as real-time interrupts and a hybrid DP-physical connector, whereby a structural

connector works in combination with the DP to maintain relative position between adjacent MOB modules. This includes consideration of wind, local currents, waves, and other disturbances.

UCB has completed a set of virtual test cases, organized in terms of operational scenarios and operating environments. For each operational scenario there are several operating environments that include the following metocean disturbances:

- First-order wave-frequency motions
- Steady wave diffraction forces
- Slow drift diffraction forces
- Current drag
- Wind drag.

Physical Demonstration Model Tests. A physical demonstration is underway to confirm virtual controller performance with reality. The demonstration uses three 2-meter (6-foot) long semisubmersible modules to capture the basic physical aspects of multi-body positioning (Figure D-19). The model scale (1:15) is small enough to allow the three modules to float in an indoor model basin at the University of California, Richmond Field Station, but large enough to carry the appropriate control computer, actuators and sensors.

Major functional subsystems include a global positioning system, local positioning system, and azimuth slew thrusters. The modules are kept in alignment and properly positioned with respect to one another exclusively by the use of custom-built azimuthing thrusters. There are four thrusters per module, and they can each be rotated 360 degrees to produce thrust in any direction in the horizontal plane. The scaled thrusters that we use in the laboratory test-bed must be controlled to emulate the performance of the full-scale units.

An important element of the planned physical experiment is the determination of the location of the semisubmersible units in the water (i.e., global position) and with respect to one another (i.e., relative position). After a survey of current sensing technologies and available off-the-shelf systems performed, a laser tracking system was identified as a suitable candidate for measuring global position. Similarly, module-mounted ultrasonic position sensors will be used to measure relative position.

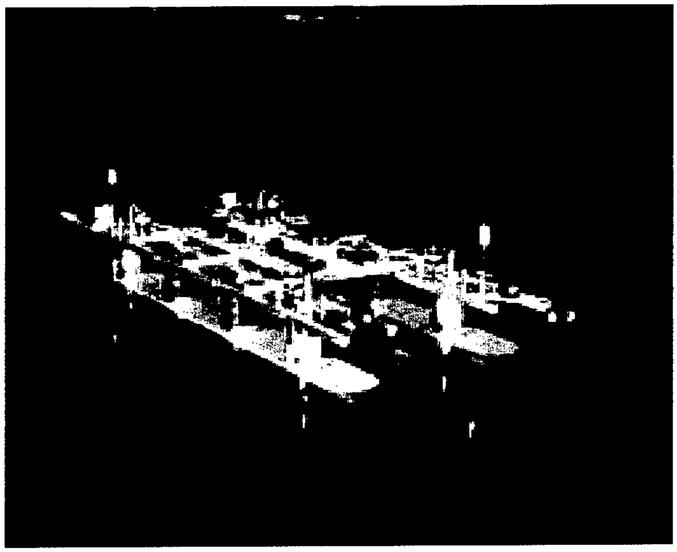

Figure D-19. One Module of the DP Physical Experiment.

Issues Remaining to be Resolved. UCB recommends a follow-on physical experiment prior to fielding a prototype scale multi-module dynamic positioning system. The small-scale experiment results to be collected in this effort are intended only to demonstrate performance aspects of the new nonlinear DP controllers. UCB chose a modeling scale that was just large enough to avoid surface tension and capillary wave problems, knowing that thruster characteristics, thruster-thruster interactions, thruster-hull interactions, and viscous drag would not be necessarily representative.

An experiment with a much larger model set and realistic thruster performance in a controlled-environment of model testing basin would be the next logical step in validating stationkeeping and navigation functions. If model scale is chosen to provide for correct thruster scaling, a scale of at least 1/66 is needed. This scale produces a MOB module that is 4.1 meters (13.6 feet) long and that weighs about 1040 kilograms (2,290-lbs).

This model may be difficult to test indoors (in a model testing basin) since the assembled MOB will be in the order of 24 meters (80 feet) long. Therefore, an outdoor test may be necessary, possibly using the same semisubmersible units as for intrinsically related hydroelastic testing at NSWC-CD (see Appendix C, Section 3.2.2). The challenge of producing steady and transient wind, wave, and current excitations with accurate spatial and temporal characteristics will increase as the scale increases, and will be a major factor in the selection of a scale and site. Finally, the hybrid connector/DP arrangement could also be physically included in the physical model.

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3.2.6 Pneumatically Stabilized Platform (WBS 4.2.6)

3.2.6.1 Resource

Float Inc. (Float) of San Diego California was the prime contractor and remains the principal promoter of pneumatically stabilized platforms. Several subcontractors to Float had major roles in the work. The University of Hawaii along with related consultants at Ocean Engineering Consultants (Hawaii) developed a VESDYN hydrodynamic model of the platform. Weidlinger Associates, Inc., developed a FLEX structural model of the platform. The Offshore Model Basin (California) along with independent consultant Neil Brown conducted the scale-model tests of this platform concept.

3.2.6.2 Advancements

Response Mitigation Methods. Because of their semi-transparency to waves, semisubmersible hulls are effective at minimizing the amount of wave and other metocean energy that excites the hull. This passive method for achieving low motions and low structural stresses forms the basis for most MOB platform concepts. In contrast, more active methods for mitigating (reducing) the response (dynamic motions and forces) are also possible.

The MOB program pursued one such active method, namely a pneumatic method for counteracting the incoming wave energy. The Pneumatically Stabilized Platform (PSP) uses active air movement between buoyancy chambers to reduce the dynamic motions and forces of an ocean platform. The partially air-filled buoyancy chambers of the PSP have bottoms that are open to the water to allow waves to surge in and out as shown in Figure D-20. The air is allowed to flow between neighboring chambers through orifice openings if pressure differentials develop due to wave action or platform motion.

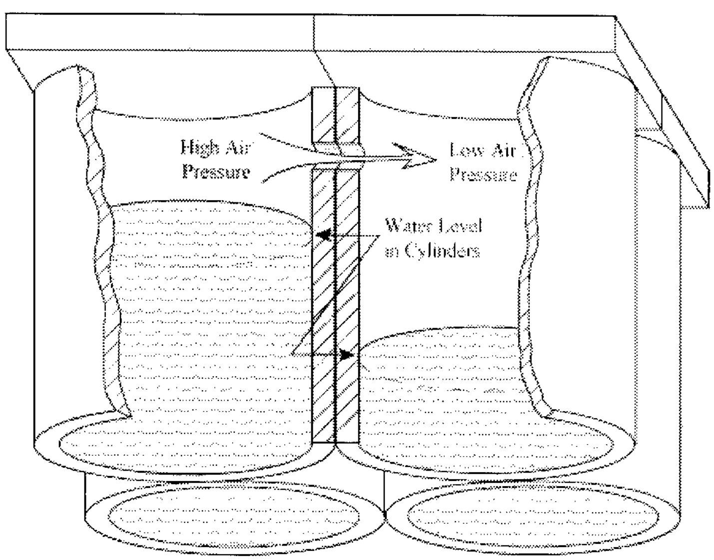

Figure D-20. Four Buoyancy Chambers for the Pneumatically Stabilized Platform.

In theory, the PSP rectifies the dynamic wave forces that act cyclically on the hull of the PSP into a rather constant buoyancy force that supports the platform. Reduced platform loads and a relatively calm lee side for cargo loading result. Load reduction occurs due to the elastic air pockets and its load redistribution.

Accomplishments. Float and its subcontractors developed simplified numerical models suitable for simulating some of the basic aspects of pneumatic stabilization. The VESDYN hydrodynamic code uses boundary element methods to compute the loading on a structure due to wave action. The FLEX structural response code uses finite elements to compute the structural stresses in the platform. FLEX is a time domain code that allows direct incorporation of nonlinear airflow. Float added linearized airflow to the [linear] VESDYN code to approximate the harmonic pressure variations between neighboring floatation cells as an equivalent harmonic. Float built a representative small-scale model of a pneumatically stabilized platform and tested it in a wave tank (Figure D-21).

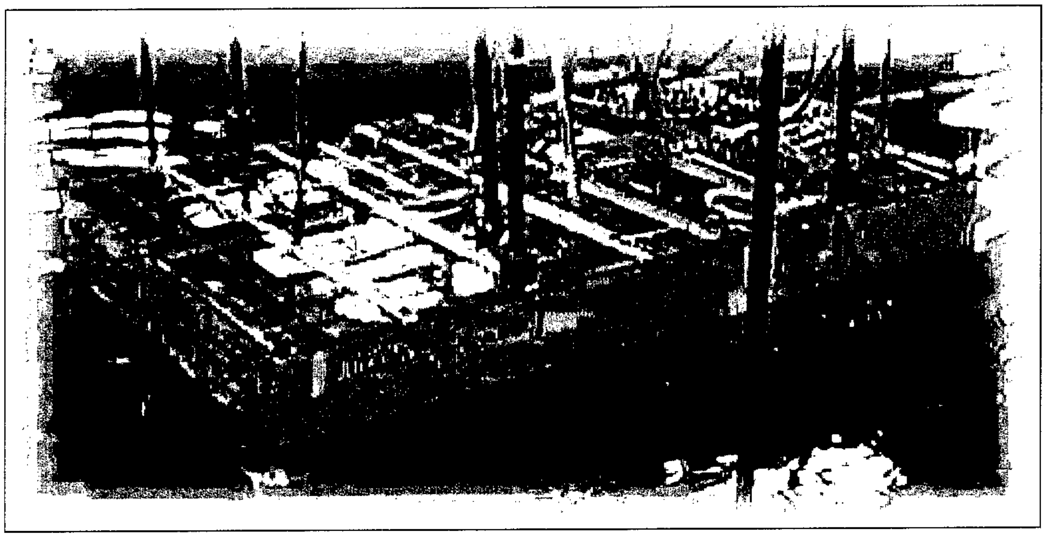

Figure D-21. Model Test Structure for Pneumatically Stabilized Platform.

In summary, Float's efforts resulted in five key findings.

- Model tests showed that intra-cylinder airflow results in substantial reductions and distribution of internal loads.
- Measured wave attenuation of a PSP was greater and more rapid than calculated. Direct measurements showed that for wavelengths less than the platform length, waves were reduced as much as 95%. Even waves several times the platform length were reduced nearly 50%. These reductions generally occurred before the fifth cylinder inboard from the front of the platform (for head seas).
- The response of the PSP depends not only on wave excitation but also on the mass of the water column, the air pocket stiffness and the air pressure distribution. This provides a useful tool to tune and minimize the dynamic response of the PSP to a particular sea state.

- A 500 X 5000 ft PSP capable of meeting the requirements of the MOB program can be constructed as a single monolithic structure.
- The simplified (linearized) computer models underestimated wave attenuation and therefore overestimated platform motion and internal stresses.

Usefulness to MOB. Assessments of a PSP are very dependent on size and configuration. The long, wide platform has greater wave attenuation and stability than a small platform. Stability for a narrow platform under static sea conditions is provided by direct displacement of the interstitial volumes and cylinder walls. Segregating airflow in the periphery cylinders can further enhance the stability if required.

Float feels that there is still much to learn about pneumatic stabilization technology before an optimum PSP can be designed. However, they also feel that there is enough known to design and construct a (less than optimum) platform that will assure the safety of personnel and assets with respect to extreme storms and other external threats.

A PSP is inappropriate for use as a full MOB platform concept because it fails to meet the minimum acceptable 12 knot mobility requirement during transiting. As a massive blunt-faced barge-type structure, a PSP cannot possibly be expected to approach the transit speeds required of a MOB. If the mobility requirements are relaxed, the PSP technology becomes more competitive as an operating ocean platform.

Active motion mitigation is very useful for improving the rate of cargo transfer to and from a MOB. PSP technology is useful for reducing the motions of a cargo transfer barge or creating desired motion behavior for an artificial beach. The artificial beach would be useful for bringing Air-Cushion Landing Craft (LCAC) on board the MOB.

Issues Remaining to be Resolved. The PSP concept achieves reductions in dynamic motion and force but at the cost of decreased static stability. Hydrodynamic stability, which is not traditionally considered in offshore platform design, is critical for this type of platform. In theory, the pneumatically stabilized platform may remain stable only with efficient movement and control of the airflow between chambers. At present, the results from analytical models, numerical models, and test data are insufficient for accurately predicting the efficiency of this airflow control and thus the feasibility of the PSP's response mitigation.

As with all modeling efforts, a number of limiting assumptions and approximations are embedded in the current set of simulation tools (VESDYN and FLEX) that have a large effect on the accuracy and efficiency of PSP calculations, namely linearized airflow and ignorance of the flexibility of the hull. Therefore, these issues need more study.

Float's ability to model the actual behavior of a PSP would be significantly improved if the simulation tools included the direct coupling of the structural and hydrodynamic response. Existing coupled methods in the frequency domain require the linearity of both the structural and hydrodynamic models. Existing coupled methods in the time domain are based on a convolution of the frequency domain solution, and therefore, also impose the assumption of linearity. Instead, a fully coupled, time-domain simulation tool is needed to account properly for the nonlinear airflow and compression. Lacking that, the basic theory for air movement between chambers, platform motion, and wave attenuation under the PSP is still somewhat unclear.

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3.2.7 Suction-Pile Anchors (WBS 4.2.7)

3.2.7.1 Resource

South Dakota School of Mines and Technology (SDSM&T) was the main investigator with some centrifuge model testing at the Daewoo Institute of Construction Technology in Korea. This work is ongoing and scheduled for completion in Spring 2001.

3.2.7.2 Advancements

Perspective. When operating in shallow water, all MOB platforms will benefit greatly from a mooring system to maintain station (rather than continuously operate a dynamic positioning system). A mooring restraint system is also necessary during lay-up and for all occasions when it is necessary to shut down power systems.

The ideal anchor for a MOB would have an omnidirectional and large holding capacity, work in a variety of soil types, and be relatively efficient (or it would be too heavy to handle). Providing uplift would be beneficial because it would save a significant length of line if the MOB was mooring in deep water, as would the ability to easily retrieve it for resuse. A suction pile type anchor is the only known anchor type that satisfies these criteria. This type of anchor is basically a hollow, vertical tube, closed at the top, that will embed itself into the seafloor utilizing suction pressure (Figure D-22).

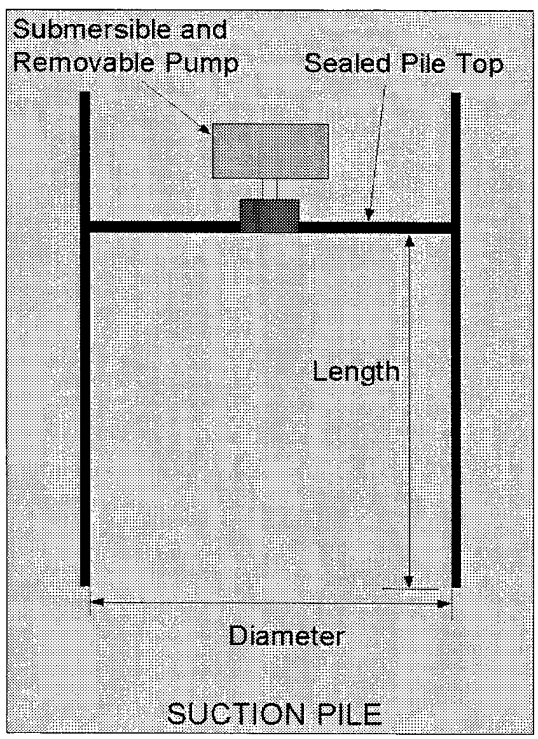

Figure D-22. Cross Section through A Suction Pile Anchor.

The single-point mooring with a suction pile anchor represents a recent industry trend for deep-water moorings. As shown in Figure D-23, a single-point mooring allows the MOB to weathervane. This rotation minimizes the system forces to metocean excitations as they pass over a MOB. Suction pile anchors have been installed with diameters up to 32 meters, typically with a relatively short length to diameter ratio.

Although the offshore industry routinely use suction piles, currently available design methods are mostly empirically-based. Therefore, more general methods of design and analysis needed to be developed before this innovative technology can be used for mooring a MOB anywhere around the world.

SDSM&T reviewed suction pile mooring technology, developed analysis and design methods, and provided validation through experiments to study the resistance and installation efficiency of suction piles. SDSM&T uniquely focused on the performance of the suction pile anchor and on its interaction with the mooring line.

Analytical Study. SDSM&T completed an analytical performance study using the three-dimensional finite element method for the pile and seafloor soil. Analyses included elastic and elasto-plastic characterizations of the seafloor soil to identify the most efficient cross-section of suction piles in sand and clay soils under various externally applied loading conditions.

The analytical solution of the suction pile installation describes upper and lower bounds of the applicable suction pressure at any given step, i.e., the pile penetration depth. The lower bound of the suction pressure is dictated by the soil strength, since the suction pressure must be large enough to overcome the soil resistance for further penetration. The upper bound of the suction pressure is determined by the instability of the soil inside the pile, since the pile installation becomes useless if liquifaction of the sand or plugging of clay occurs inside the pile anytime during the installation.

The analytical solution first determines the initial pile penetration depth due to the self-weight of the pile and superstructure. It then estimates the upper and lower bounds of the suction pressure that can be applied for further pile penetration without creating soil instability. This procedure continues until the pile installation is complete.

Modeling Tools. SDSM&T developed computer model(s) to understand the complete system response of the single point mooring system with a suction pile anchor and mooring line. For computing the suction pile performance, the computer models included the effects of the suction pile size/shape, location of a flange at the top, layered seafloor soil conditions, and point of mooring line attachment.

For computing the mooring line geometry and tension forces, the computer models allow for various materials for mooring line segments, layered seafloor soil conditions, interaction with the seafloor surface, seafloor soil elasticity, and sinkers. Published field and model-scale centrifuge test results were used to calibrate these new computer models.

In summary, these modeling tools can be used for three MOB design purposes. They can be used to optimally design the suction pile anchor. They can identify whether a full and successful installation of any given suction pile is feasible or not for given site conditions. And, they can be used in the field to guide the actual installation of suction piles.

Experimental Validation. SDSM&T completed small-scale laboratory model experiments on suction pile installations in sand and clay to identify limits on size, suction pressure, and versatility in a variety of

soil conditions. They performed eighteen and 24 sets of model tests on sand and clay, respectively, utilizing various pile diameters, surcharge weights, soil strengths, and initial pile penetration depths. Each set consisted of three to five identical tests to minimize any potential error.

The Daewoo Institute of Construction Technology completed some centrifuge model tests on the suction pile installation and the mooring line tension. (The model-scale accelerations in a centrifuge are used as an apparent force of gravity to represent the full-scale behavior.)

A collaborative field test of suction piles was conducted by NFESC off the Port Hueneme, California, to provide additional medium-scale experimental data, and used by SDSM&T to further validate their new models.

Issues Remaining to be Resolved. Although the analytical solution of suction pile installation has been calibrated and validated with small-scale laboratory and medium-scale field experiments, for the analytical solution to be complete it must be validated through full-scale field experiments. Full-scale field experiments are however extremely costly. Instead, well-controlled laboratory centrifuge model experiments can be run to replace the full-scale field experiments. More centrifuge model tests on suction pile installation in sand and clay need to be conducted to completely validate modeling tools and their analytical solution.

Static and dynamic loads along the vertical, horizontal, and inclined directions are expected from the mooring of a MOB. It is particularly important to characterize the effect of the negative pore water pressure in providing the reverse bearing capacity, which is known to contribute to the increase in the bearing capacity of suction piles under dynamic loads. Again, inexpensive, small-scale laboratory experiments should be conducted first to calibrate the analytical solution method that is currently being developed. The solution then needs to be validated through centrifuge model tests and at least medium-scale field tests.

Finally, the various modeling tools that have been or will be validated need to be put together as a comprehensive software package, useful as a complete design, analysis and installation guide for suction pile anchors and their mooring lines.

3.2.7.3 Products

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3.2.8 Lightweight Decking (WBS 4.2.8)

3.2.8.1 Resource

Atlantic Research Corporation (ARC) in Virginia is the main investigator. Under subcontract, the Georgia Institute of Technology provided laboratory testing, and the Virginia Division of Highways provided a traffic test bed for field testing of decking panels.

3.2.8.2 Advancements

ARC assessed alternative structural material and configurations to achieve significant reductions in weight of platform and bridging decks. They selected fiber-reinforced fabric configured into a structural panel. As shown in Figure D-24, the panel contains a triangular arrangement of internal elements sandwiched by upper and lower face sheets. End plates (not shown) isolate the internal structure from the environment.

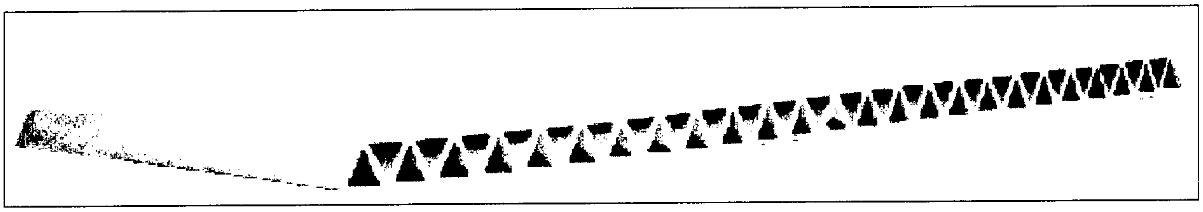

Figure D-24. Composite Decking without End Plates to Show Internal Structure.

The internal triangular elements are fabricated using a single thick ply of 3D-braided fiberglass textile drawn through a pultrusion die and rigidized with vinylester resin. The triangular pultrusions are bonded together with the face sheets, using Plexus adhesive. The assembly is optimum weight for a plate over a span because the triangles carry the load with truss action and the face sheets carry the load in bean bending.

The edge supported composite deck panel can span up to 3 meters by 9 meters at a weight less than 100 kilograms per square meter (20 pounds per square foot). The panels were designed according to the requirements of the Trilateral Code for Military Bridging and the Circular of Requirements for New Construction of Strategic Sealift Ships. ARC also developed a successful manufacturing process for fabricating the full-size panels.

The Georgia Institute of Technology tested material specimens and structural components at all levels of assembly. This included coupon, single triangle and full panel tests plus patch load tests on the panel faces to simulate tire loads. A three-by-three-meter test panel was loaded to 635 kilo-newtons (140,000 pounds) with a measured deflection of 1.78 centimeters (0.7 inches).

The Virginia Division of Highways is helping ARC field-tested the lightweight decking by providing a test bed at a weigh-station on Interstate 81 near Roanoke, Virginia. Truck and tractor trailer rigs moving at 40 mph drove over the panels. This test demonstratef the durability of the panel, particularly the sand epoxy wear surface.

Issues Remaining to be Resolved. For MOB, lightweight composite decking may have applications for portable ramps and bridging (such as inter-module bridging). Lightweight decking could provide stability advantages for some MOB concepts by lightening up the upper structure of the MOB and thus increase the meta-centric height for increased static stability. Bechtel investigated using these composite panels as decking on its MOB inter-module drawbridges and found that there was not an overall weight savings as compared to steel because the composite panels needed extra support structure. This would obviously not be the case for regular decking applications.

3.2.8.3 Products

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2. Atlantic Research Corp., Structural Test Plan For LSQ/C - Modular Lightweight Causeway Deck, 13 March 1998.
3. Brown, R.T. and A.-H. Zureick, Lightweight Composite Truss Section Decking, Third International Workshop on Very Large Floating Structures (VLFS '99), Honolulu, Hawaii, September 22-24, 1999.

3.2.9 Open Sea Cargo Transfer (WBS 4.2.9)

It was recognized early in the MOB S&T program that the ability to transfer cargo between the MOB and vessels alongside was an important issue in establishing the feasibility of a MOB meeting its operational missions. However, the issue was secondary to the primary focus of establishing the technical feasibility of a MOB (which emphasized the structural integrity of MOB). As the Program evolved, some resources were made available for investigating two aspects of open sea cargo transfer: berthing various vessels to the MOB in the open ocean, and the transferring cargo between the MOB and small vessels alongside. These efforts are described in the sections below.

3.2.9.1 Resource

The Naval Facilities Engineering Service Center (NFESC), East Coast Detachment in the District of Columbia, investigated the feasibility of mooring vessels alongside the MOB. Bechtel National Inc. (BNI) in California analyzed the wave climate near and under a MOB and investigated motion mitigation measures for small vessels.

3.2.9.2 Advancements

Vessel Mooring. The ability to transfer large volumes of cargo between ships alongside the MOB starts with berthing vessels alongside the MOB in the open ocean environment. Several challenges exist in mooring a cargo vessel to MOB. They include the need to accommodate variations in deck height, the need for fenders at the waterline, and the motion of the ship in the open sea. Fortunately, the motion of the MOB is generally insignificant in most operational metocean conditions.

NFESC conducted time-domain dynamic simulations for four representative classes of vessels that might berth to the MOB. These included a SSN-688 submarine, DDG-51 destroyer, LSD-41 amphibious ship, and CVN-68 Aircraft carrier. NFESC conducted simulations for each vessel at a variety of sea states to evaluate both the moorings and mooring line behavior in operational and survival conditions. Wind and current effects were included in the simulations.

NFESC also considered different berthing materials and equipment, including a variety of mooring lines and the use of "smart" constant tension winches. The specific goals were to identify the type of mooring and mooring features that best minimize relative motions between vessel and MOB and provide the greatest safety. The results of this study showed that it is feasible to berth many types of vessels alongside the MOB utilizing existing technology. The work also defined specific features for MOB vessel restraint systems that greatly enhance operational capability.

Wave Field alongside a MOB. Most missions for MOB require the offloading of cargo from MOB to small lighterage, such as ocean-going lighters, through Sea State 3 conditions. These smaller vessels respond to lower wave conditions more so than larger vessels, making berthing and cargo transfer at the MOB a potentially even greater challenge for these small vessels.

Hydrodynamic studies confirm that a MOB semisubmersible actually amplifies waves near and under the deck and columns. As seen in Figure D-25, 6-sec waves incident from 30 degrees off the bow of a MOB module actually amplify their height on the lee side of many of the columns. Shown better in the original color version, the gray scale of the figure indicates levels of amplification of the wave height at the water surface around and between the columns of the MOB module. Bechtel conducted a linear diffraction analysis of five different configurations for a single MOB module to investigate the wave field for a range

of wave periods and directions and for various MOB configurations.

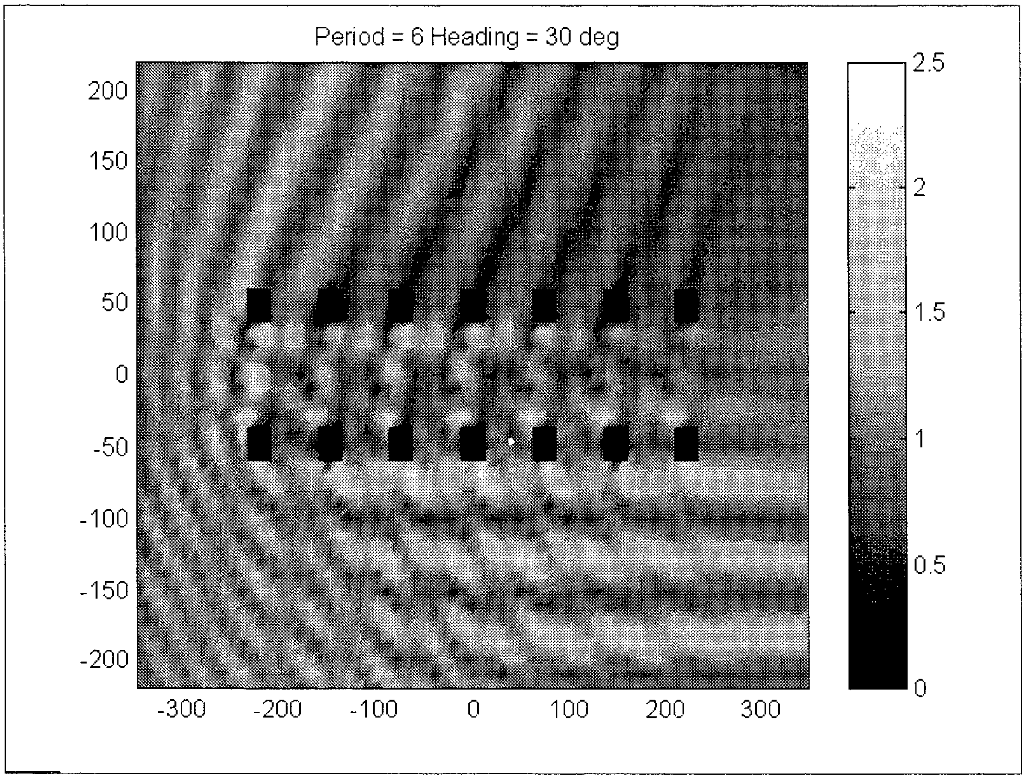

Figure D-25. Typical Wave Surface Contour Plot.

The configurations differed in the number and spacing of the columns. The results showed no discernable trend for either wave period or direction, but did confirm that wave motion is amplified at various locations adjacent to the MOB. Only one of the configurations evaluated showed a consistent reduction in sea conditions, but that configuration consisted of many closely spaced columns. With such closely spaced columns, an unacceptably high global force acts on the MOB.

The hull modifies the wave field around the MOB in a way that causes very high waves in some locations and very low waves in other very nearby locations. In fact, wave height in any given location is very sensitive to specific wave frequency and direction. In other words, we cannot count on the MOB hull, by itself, to provide reliable sheltering from waves.

Local Wave Mitigation Measures. Given a potentially amplified wave environment, it made sense to investigate alternative methods for mitigating the wave environment to improve the feasibility of transferring cargo to and from small vessels alongside the MOB. The effort included the preliminary development and evaluation of two conceptual designs to mitigate the wave environment near the MOB.

The first concept is a multi-level deployable barrier structure that creates a lee for small vessels and is suitable for use in relatively low sea states (Figure D-26). Simulations show that such walls can be effective at reducing lighterage vessel motions by about one-half. While this is a considerable improvement, it is not clear whether this will be adequate for a high rate of cargo transfer. To prevent

damage to the MOB hull during larger sea states, these wall surfaces must be stored under the deck during higher sea conditions.

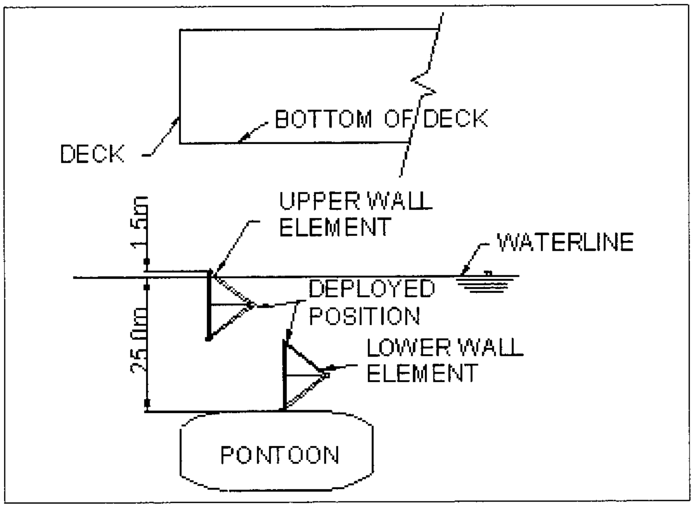

Figure D-26. Wave Sheltering Walls (sectional view).

The second concept investigated an artificial lagoon located in one of the aft bays of a MOB module. The lagoon had three protecting vertical walls and a horizontal bottom. Results of initial analyses indicated that the lagoon concept did not provide as calm an environment as the deployable barrier structure, and that it was less feasible from a structural standpoint due to weight. It was noted that a four-sided lagoon (closing the open end with a swinging door) would provide eliminate all wave motion, but would be awkward to handle.

Issues Remaining to be Resolved. The preliminary studies described above were only able to touch upon two critical issues for open sea cargo transfer. While the results of these studies indicate that cargo transfer operations are likely feasible, further assessment is needed to rigorously establish feasibility for cargo transfer at the volumes and under the environmental conditions dictated by MOB missions.

3.2.9.3 Products

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4 RECOMMENDATIONS

At the start of this Program, each platform design contractor felt that they had all of the necessary analysis tools and a MOB concept that was ready for a final design effort. Those assessments were based on the contractor's particular experience with design and operation of "similar" offshore structures.

However, other MOB participants soon raised numerous questions about the adequacy of such studies. What was the nature of metocean events and wave fields of over one mile in length? Were available linearized analysis tools adequate for calculating the metocean interaction with very large, flexible, articulated, floating structures? Could multi-module dynamic positioning at sea reliably achieved? Were methods for evaluating the feasibility and functionality of the alternative MOB concepts available? In short, there was little consensus or analytical justification for confidence that a MOB could be produced and effectively operated.

Most MOB participants believe that the ONR program has addressed these issues. They also believe that technical innovation has now progressed to the point that MOB is now technically feasible. However, this does not mean that S&T activity should be discontinued. On the contrary, the program, freed from the need to answer the question, "Can it work?" can now focus on "How can it work best?"

As such, the following potential products are recommended for future funding consideration.

4.1 Requirements and Design Philosophy

The single greatest need of the Program is an Operational Requirements Document (ORD), which would be translated to definitive mission requirements for use by designers. Different operational needs favor different MOB platform architectures, so none can be yet identified as "best" for MOB. The optimal architecture should be reconfigurable so as to be able to accommodate not only immediately perceived needs, but also those yet unseen. The answer to this need is a series of modules that could be connected to form a lengthy runway for servicing land-based aircraft or disconnected to transit and operate as individual modules. The individual modules should be large enough to meet some mission needs as single units, yet small enough to represent acceptable extrapolations from existing state-of-the-art, to survive storms at sea, and to remain constructable in existing US marine construction infrastructure.

4.2 Platform Global Response

Global hydroelastic response models are extremely important for designing MOB, particularly the more flexible concepts for MOB. The ongoing Design Tool efforts have provided guidance on the accuracy of the present tools, and how to improve these tools for future MOB concept designs. Wave run-up and air gap are only estimated with traditional design tools. Wave run-up and mitigation measures at the column/deck connections should be addressed. Slamming loads on the column steel braces must also be considered.

Because of its large size, a MOB hull may require a unique characteristics to survive. This may change the traditional approach to material fatigue estimation and to overall structural reliability. An advanced study of residual stresses and weld embrittlement in steel structures may also be required, as these effects may become more important given higher structure flexibility.

4.3 Connector Design

More work on the maximum forces in the connectors is needed to verify the established sea-state parameters that require the MOB to be disconnected to survive. These forces must include static loads from weight and buoyancy, mean and slowly varying loads from the environment and reactions from the DP system, and the wave-induced loads. Several concept design contractors suggested that only time domain based models would do for computing correct connector forces and relative motions. They argue this because the application of loads along the length of the MOB is definitely time sensitive. Finally, it would be ideal if MOB could remain connected through even the worst of metocean conditions, even though operators of MOB would still be wise to disconnect well before an approaching severe storm.

4.4 Stability of During Transit

The highly nonlinear dynamic motion of the pontoons during transit must be addressed by performing more model tests. With large deck loads placed well above the waterline for a fully loaded MOB, classical static stability estimates for such a semisubmersible may not be sufficient. Measures of dynamic stability, particularly the amount of cyclic acceleration at transit draft, become important for maintaining safety of the cargo and comfort of personnel on board the MOB; see Appendix C for more information on those studies. In addition, towing tank tests should be carried out to verify the resistance and required thruster power of an individual module during transit.

4.5 Reliability and Performance of Multi-Module Dynamic Positioning System

The stationkeeping behavior of a MOB platform depends heavily on the effectiveness of a multi-module dynamic positioning system. Such a system for MOB must operate in many modes, including positioning a single module, connecting and disconnecting a series of modules, maintaining alignment of the assembled MOB, and seamlessly switching between those modes. The ongoing work in multi-module dynamic positioning is crucial for all future design of any of the MOB system platform concepts.

Dynamic positioning is not only needed to maintain global position, but it is also needed to position modules relative to one another for MOB concepts without connectors and for MOB concepts with compliant connectors. To develop feasible inter-modular connectors, one must lower the levels of force in the connectors. To accomplish this, one must free rotation components and allow compliancy in the connector. In doing this one allows the MOB to bend. To restore straightness one must use dynamic positioning in a unique combination with the connectors. We must insure that the dynamic positioning system cannot inadvertently add unintended stresses to the connectors. Therefore, it is necessary to expand the development and testing efforts for multi-module dynamic positioning to include active interaction with inter-modular connectors.

4.6 Cargo Transfer

Considerable further studies are needed to provide for cargo transfer at the volumes and under the environmental conditions dictated by MOB missions. The following tasks are recommended to meet that goal.

Requirements Definition. More specific cargo throughput requirements encompassing specific vessels and environmental conditions need to be established for a meaningful evaluation of feasibility. In addition, the operational limits for small vessels operating at the MOB need to be determined to

adequately develop criteria for mitigation methods and determine operational feasibility at the MOB.

Consideration of Environmental Effects Other than Wave Climate. Similar to the wave environment being amplified in some locations by the presence of the MOB structure, the effect of the structure on wind and current needs to be evaluated to determine any additional adverse effects. In particular, while the columns may create some local sheltering effects, the gaps between the columns could amplify wind speeds, magnifying the loads on vessels moored to the MOB and worsening conditions for pendulated loads. Furthermore, each module shields the following one, and the resulting discontinuities in the wind and current forces due to that sheltering will challenge the dynamic positioning (DP) algorithms. Finally, additional studies into transient, spatially-varying phenomena such as internal waves and solitons are needed to insure the DP system is adequate to resist them.

Advancement of Alternative Concepts for Wave Climate Mitigation for Small Vessels. Only preliminary studies of a few wave mitigation measures could be completed under this program. It is strongly recommended that a more thorough development and evaluation of concepts for mitigating motions be completed for small vessel operations at the MOB. This investigation should consider the concepts for physically lifting small vessels out of the water and onto the deck of the MOB.

Evaluate Effectiveness of Promising Cargo Handling Concepts. Cargo management and transfer should be studied to ensure optimal effectiveness of MOB to perform its logistical functions. This includes cranes, ramps, and internal storage mechanisms. Safe and fast transfer of cargo, vehicles and troops to/from MOB and a multitude of cargo transport types will be of utmost importance to the operability of a MOB. The ability of MOB to provide support for the execution of an amphibious assault operation is highly dependent upon a rapid conveyance of cargo and vehicles to the theater of action.

4.7 Construction and Repair

Methods for constructing and repairing a MOB need to be further investigated. The individual MOB modules are generally too large to bring into conventional dry docks. Therefore, in-situ methods for constructing, monitoring, and repairing ultra-large hulls may be important for feasibility of a MOB. This may include at-sea methods for joining sections of a MOB module, new underwater welding processes, methods for underwater concrete repair, techniques for repairing the outside hull from inside, and caisson concepts for providing local ship husbandry.

4.8 MOB Mooring

Deep-water mooring systems of the required magnitude for MOB have never been designed but are within reach. Innovative research efforts to develop viable concepts for single point moorings suitable for single or multiple MOB modules and used either independently or in conjunction with dynamic positioning are needed. Research in prediction of single-point mooring response, fundamental rope mechanics principles, new mechanisms for terminating the ends of large diameter synthetic lines, and methods for nondestructive testing of large mooring lines is needed.

4.9 Operational Demonstration

Several of the MOB system designers have suggested the need for full-scale operational demonstrations. Such operational demonstrations would conceivably focus on connectors, dynamic positioning, transit stability and all of the other topics lifted above. However, well-prepared smaller scale experiments are

always more manageable and more cost effective than a full-scale experiment. Therefore, full-scale tests are not generally needed for basic science and technology issues. However, there are a number of interface issues with humans and vessel/lighterage, and full-scale demonstrations are recommended for those. An excellent objective for a demonstration would be to show that military personnel could load and unload a MOB, and connect/disconnect modules of a MOB.